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NAME OF AUTHOR: Garry James McCue

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SMALL-SCALE WINDPOWER FOR LESS-DEVELOPED AGRICULTURE

by

GARRY JAMES McCUE ©

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Small-Scale Windpower for Less-Developed Agriculture," submitted by Garry James McCue in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Natural power sources such as the wind have often been suggested as one (if not the most desirable) solution to providing stationary power. This thesis investigates the production of wind-electric power for small-scale application in the agricultural sector of less-developed countries.

Windpower is introduced in historical perspective and the implications of its use in a less-developed setting are discussed in detail. A prototype wind-electric plant was designed, constructed and tested. The two major conclusions that have been reached are as follows:

1. A small-scale wind-electric plant may be built entirely with expertise and materials already available in less-developed countries.

2. Unless materials used for plant construction are obtained very cheaply, the cost of energy from the wind will be much higher than energy available from more conventional sources. As a result, windpower could be best used in areas where alternative power sources are either not available or would be very expensive to provide.

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1.1 PURPOSE, METHODOLOGY AND OUTLINE

The purpose of this thesis is to investigate windpower for use on small farms and in rural communities of less-developed countries.

Windpower is considered in historical perspective so that its appropriate use may be better defined. This concept of "appropriate technology" is then applied to the designing of a prototype. Discussion of subsequent construction and testing of the prototype follows.

The remainder of this chapter relates the history of windpower and its development as a power source in agriculture. Chapter 2 discusses windpower use in less-developed countries and introduces the concept of "appropriate technology". Chapter 3 is concerned with windpower theory. Chapter 4 introduces the wind-electric system and here the detailed design of a prototype is carried out. Chapter 5 includes experimental procedure and interpretation of results. Chapter 6 presents conclusions. Appendix 1 includes relevant figures, Appendix 2 identifies symbols, Appendix 3 lists formulae and Appendix 4 contains photographs of the prototype.

1.2 HISTORY OF POWER IN AGRICULTURE

1.2.1 Early Man

Before 8,000 B.C. man was a rare species (20). Equipped with few natural defences, he was only able to survive by his agility and wit. The use of fire, introduced just prior to this period, was probably the only advancement significant enough to have saved him from extinction.

Man of the late Palaeolithic Period (Old Stone Age) lived by hunting and food gathering and used a number of tools to assist in these ventures. Crude stone axes, knives and scrapers were used to supplement hands and teeth and at least two important machines were known: the bow and the spear thrower (20). As a nomad, Palaeolithic Man was constantly on the move in search of food and his life was far from secure.

1.2.2 The Beginnings of Agriculture

By the beginning of the Neolithic Period (New Stone Age), about 8,000 B.C., man began to take shelter in caves, as the climate had become progressively colder. As he moved from place to place in search of food, man gradually became aware of the advantages of settlement. Hunting and food gathering in a familiar area was much more efficient than it was in unfamiliar territory. From such "settlement" evolved the domestication of animals and the rudimentary development of carpentry and pottery.

A portion of man's diet had always been the seeds of certain tall grasses. Upon permanent settlement, man noticed that these grasses traditionally grew in the same general area year after year and this knowledge provided for a more stable food supply than meat, obtained at irregular intervals. It is supposed that the first step towards agriculture occurred when some seeds brought to his cave, where they could be eaten in safety, were dropped at the entrance and grew into a crop on man's very doorstep*.

Man thus learned to sow and from this point forward progressed much more quickly. With his food supply from crops and domesticated animals relatively secure, man now had time to consider other matters. The transition from food collection to food production was the most significant advance of this period.

1.2.3 Grain as Food

With the adoption of grain as man's staple, food preparation became more important. Previously the only preparation required had been the roasting of meat on a spit over an open fire, but grain was not so easily prepared. Even fruit could be eaten directly, but hard kernels of grain were not ingested so readily. At first, when

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*Of course this accident must have occurred many times before the realization that the seed was the source of the new plant finally dawned.

only small amounts of grain were eaten, it was possible to chew it, like fruit, but as grain became a more dominant part of man's diet, some method of making it more palatable became necessary.

At first grain was crushed between two stones into a coarse flour and later, with the development of pottery, was boiled in water over an open fire to make gruel. The combination of these two methods, milling and cooking with water, led to the development of bread. Later the mortar and pestle was developed and provided a means to make better quality flour. By 2,500 B.C. the pounding of grain into flour was superceded by the invention of the saddle quern, whereby grain was ground by working a rubbing stone backwards and forwards across a saddle-shaped stone base (20,33)*.

The saddle quern was in common use in Egyptian households at this time and it remained the most advanced form of flour milling machinery until the discovery of rotary motion, about 600 B.C. (20). In the rotary quern, grain was ground via friction between two circular stones, the upper stone revolving about a pivot projecting from the center of the lower stone. This method saved considerable labor and produced a much finer flour. However, even with these "new" developments, the grinding of grain

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*The mechanism for grain milling was now grain kernel shear, via friction, instead of compression failure, via impact.

for the family was a time-consuming and strenuous task which had to be done daily by the womenfolk of each household.

1.2.4 Domestication of Animals

Until about 3,000 B.C., the only power available to man was that of his own muscles. Initially animals--cattle, sheep, goats--were domesticated only in order to provide a ready food source in the form of milk and meat (and perhaps, in the case of the dog, companionship and help in hunting wild game). When man became a farmer and tilled the soil, he soon saw the advantage in putting the larger animals to work. The harnessing of animals, first to the plow and later to the cart, was the first instance of men using power, other than that of their own muscles, to do their work for them (20). Later, draught animals were employed to power large rotary querns and, by the time of Christ, commercial milling establishments were common throughout the Roman Empire.

1.2.5 The First Use of Windpower

The first source of power other than that of men and draught animals was the wind. Men learned that the wind could help propel a boat across open stretches of water. The development of the sail, credited to the Egyptians of about 3,500 B.C., opened the way to marine navigation, and by 3,000 B.C. the Eastern Mediterranean was being freely navigated by wind-powered ships (20).

Early Egyptian drawings show a reed boat, equipped with a square sail, used for transporting goods up the Nile with the prevailing winds. Ship propulsion via the wind remained the dominant method of marine power until superceded by the development of the steamship some 5,000 years later (20).

No evidence is available that suggests windpower was used in agriculture during this period and it is likely its first use in agriculture did not occur until much later.

1.2.6 Waterpower in Agriculture

From the cyclic flooding of the Nile, the earliest Egyptian farmers had realized the importance of an adequate water supply for their crops. During dry periods in Egypt, before 1,500 B.C., irrigation was practiced using man-powered water lifts based on the principle of the lever. With the development of the wheel and the introduction of draught power, the ox-driven water wheel carrying a continuous series of pots came into use (about 200 B.C.)(10). By 100 B.C. the Greek inventor, Pollio Vitruvius, adapted the Egyptian "wheel of pots" to drive itself from the force of the water flowing past the wheel. This eliminated the need for animal power in some cases (when streams were available and flowed quickly enough) and is the first recorded use of other than muscle power in agriculture (20).

The use of waterpower to grind corn was first introduced by the Greeks, about 85 B.C., in the form of a vertical-shaft mill supported over a fast flowing stream. On the lower end of the shaft, a wooden impeller fixed to the shaft was rotated by force of moving water and drove a rotary milling stone fixed to the shaft above. With such an arrangement, however, the speed of the millstone was the same as the speed of the impeller and this was a considerable disadvantage. Later, with the introduction of suitable right-angle gearing, the horizontal-shaft waterwheel was developed and in common usage by the Romans before the time of Christ (33). By 550 A.D. Rome was almost totally dependent on waterpower for flour milling (7). The watermill concept spread throughout Europe and according to the Doomsday Book of 1086 there were already 6,000 watermills grinding corn in England by this date. Thus, the watermill became man's first engine.

1.2.7 Windpower in Agriculture

The first recorded use of windpower for agricultural purposes was about 650 A.D., in the District of Seistan located between Persia and Afghanistan (10). There, all-wooden windmills were designed to grind corn. These were built with the windwheel at ground level such that its vertical axle ascended to the second story, where a circular millstone was directly driven in the same manner as the first watermills. Speed control of this

windmill was accomplished by a series of shutters around the windwheel, at the base, which could be arranged to expose more or less of the wheel to the wind.

In China a similar ground-level, vertical-axis windpower mill was constructed at a later date and was far more efficient than its Persian counterpart (33). The problem of attaining continuous rotary motion from the pressure of the wind on a plane surface was solved by allowing the sails of the windwheel to rotate such that they would move edgewise against the wind and then turn to take the full force of the wind for half of each rotation. This arrangement also had the advantage of being able to utilize wind equally well from any direction, without adjustment.

The windmill* was introduced into Europe in the 12th Century A.D., by which time the watermill was already in common use (20). The major advantage of the windmill was that it need not be built next to flowing water and, indeed, was most often installed on hilltops where wind speeds tended to be greatest. The advantage of the watermill was that more power was available from streams than from the wind for comparable installations. Also, waterwheel power output tended to be more constant than windwheel power output. In addition, the energy available to

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*The term "windmill" is used in the colloquial sense whereby any device powered by the wind is called a windmill, although it may or may not power a mill.

the waterwheel is in the form of potential energy which can be stored simply by erecting dams to control the water flow rate, but the energy of the wind is in the form of kinetic energy which is not easily stored*.

In England, windmills were mainly used to produce flour and grit for human consumption, and grouts (husked corn) for animal feed.

In Holland, windmills were developed to pump water from the land reclaimed from the sea, and the Dutch windmill performed this task admirably for more than 500 years.

In Denmark, many farmers built private windmills of their own (called housemills) which were usually mounted on the barn and used for many tasks, including grain thrashing, wood cutting and water pumping. The first housemills were primitive homemade wooden structures but by the 1890's industry was producing iron and steel versions on a massive scale to supply the agricultural market. These mass-produced windmills were characteristically capable of producing about 3 to 5 kw and many were self-governing to rotate at constant speed. In 1890 a State Windmill Station was set up at Askov by the Danish Government under the direction of Professor P. La Cour, and much was done to

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*It should be emphasized that watermills and windmills were not competing power sources as such: if there was flowing water nearby waterpower was always the first choice, but if wind and not water was available then windpower could be used. Of course, if neither wind nor water power was available, then it became necessary to revert to muscle power supplied by men or draught animals.

promote the use of windpower and develop windpower technology (17).

The advent of electricity provided yet another use for windpower. As early as 1881 the idea of using the wind to produce electric power had been put forward by Sir William Thompson (later, Lord Kelvin). By 1910, several hundred wind-electric plants of from 5 to 25 kw had been erected in Denmark, according to La Cour's design. Each plant was provided with storage batteries to compensate for the irregularity of the wind thus "storing" wind energy for the first time. These first small-scale, wind-electric plants were a great success and introduced to the farmer the utility and versatility of electric power on the farm (17).

During the 1800's, windpower in America developed parallel to that of Europe. By the 1920's many farms in Canada and the United States were using windpower to pump water or provide electricity. Because of the large land holdings and thus the greater distances between neighbours, the large communal mills of Europe (which had also been symbols of the feudal system in many countries) were never popular in America. The smaller windmills, especially the multi-bladed, low-speed type, provided water for the farm and did much to develop the great agricultural potential of North America.

> The importance of this movement (the use of windpower on farms), inaugurated by our inventive farmers, is made manifest in that many acres of garden truck, fruit land and

> even farm land are irrigated; that stock is supplied with water; that ranchers and sheep herders are benefited; that dairy products are increased and improved and that the comfort of the village and the rural home is often enhanced.
>
> (1-page 5)

Such was the contribution of windpower to the development of agriculture.

1.3 MODERN POWER SOURCES IN AGRICULTURE

1.3.1 Heat Engines

With the coming of more reliable power sources, the use of windpower declined. Steam power, introduced in the early 1800's, soon became important not only for grain thrashing and water pumping, but also for cultivation of the soil. Gradually steam power replaced wind and muscle power on the farm.

Steam engines differed greatly from earlier prime movers in that they were more reliable and more powerful than natural power sources and could produce power on demand. But steam engines also had to be fueled, distinguishing them from natural power which had left the environment essentially unchanged. Now trees had to be cut, coal mined and oil supplied to keep the steam engines running.

In the early 1900's internal combustion engines were introduced to agriculture. They were lighter and cheaper than the steam engine. The adoption of the internal combustion engine quickly led to the industrialization

of the developed world and this engine has yet to be replaced as the major prime mover in modern agriculture.

1.3.2 Electricity

Rural electrification in the developed countries began about 1910 with the use of steam engine, internal combustion engine, and wind and water driven electrical generators. The utility and versatility of electric power on the farm led to its universal adoption by agriculture. Extensive electrical distribution systems in America and Europe soon eliminated the need for each farm to produce its own electricity and at present almost all farmers in the developed countries are supplied with electric power from such networks.

1.3.3 Windpower

At present there are still a few small windmills in North America in operation on the farm, mainly used to pump water for livestock, but they are no longer common. In Europe, only a few large size windmills are still in working order and these serve mainly as tourist attractions. In some areas there are a few smaller windpower plants used for the generation of electricity and water pumping on European farms, but these no longer make a significant contribution to total farm power requirements.

1.4 WINDPOWER: PRESENT AND FUTURE

1.4.1 Recent Windpower Developments

In recent years, windpower development in the developed countries has concentrated on the production of electric power. The largest windpower plant built in America, to date, was the Smith-Putnam wind turbine installed in 1941 on Grampa's Knob in Vermont. The support tower of this mammoth aerogenerator was 110 feet high. Its 1250 kw generator was driven by a 175 foot diameter windwheel. In 1945, after only a few months' operation, this machine was wrecked by high winds and was never rebuilt (17). During World War II, a number of 50 to 70 kw aerogenerators were built in Denmark by F. L. Smidth of Copenhagen to feed electrical power into local distribution lines, and many of these machines are still in operation (17). In Great Britain a 100 kw experimental machine with an eighty-foot, two-blade propellor was operated successfully by 1955 near St. Albans, England (45). In 1958 this machine was transported to Algeria and is still undergoing long range testing (46). Germany, France and the U.S.S.R. are at present all developing large and small-scale aerogenerators and most recently, the National Science Foundation in the United States announced plans for the construction of a 3,000 kw aerogenerator as the first step of a multimillion dollar research and development scheme to produce alternates to fossil-fuel electrical

energy production.

In the less-developed countries very little has been done to promote the use of windpower in agriculture. A number of organizations are supporting research in India but, to date, little has been done to get windpower onto the farms (27, 37, 38). The Brace Institute in Canada, associated with McGill University, has been developing a windpower plant for use in less-developed countries. The initial results from testing windpower irrigation in the Caribbean indicate a technical success but the economics of this particular application are not encouraging*.

1.4.2 The Future of Windpower

Within the past few years there has been a renewed interest in the wind as a source of energy. Rapidly increasing fuel costs and concern for the environment are two factors contributing to this interest in developed countries. The United States has just launched a 30 million dollar windpower program and it is expected that other developed countries will follow suit (5).

In the less-developed countries, the tremendous influence that the introduction of natural power sources such as wind and water can have on development is recog-

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*One interesting result has been that, under tests in the Caribbean, it has been shown that the relatively unsteady water supply produced by the windpower plant has not resulted in reduced yields compared to yields having a steady supply of irrigation water provided by diesel power.

nized. In the rural areas of many of these countries the only power available is still muscle power. It is thought that the introduction of natural power sources can do much toward more rapid agricultural development (34).

2. THE RATIONALE FOR WINDPOWER USE IN LESS-DEVELOPED COUNTRIES

2.1 AGRICULTURE IN LESS-DEVELOPED COUNTRIES

2.1.1 The Present Situation

The majority of those who work in the agricultural sector of the less-developed world live at the lowest socio-economic level of existence--the so-called "subsistence level". In economic terms this means that productivity is stable at a level too low to produce a surplus of primary agricultural commodities sufficient to provide for improved methods of production. This basic inability to accumulate capital is one major obstacle to economic development. In social terms, those living at the subsistence level have little control over their destinies, living at the mercy of the elements and the more powerful who control the prices paid for agricultural goods.

In the past it was postulated that the injection of sufficient capital into the agricultural sector*

*Note that the agricultural sector includes not only the subsistence farmer but also corporate farmers as well as those associated with government and other agricultural agencies. Probably little capital has ever filtered down to subsistence farmers.

would stimulate economic growth and thus lead to development, but this has not proven to be so (31). In order to better judge what may or may not be accomplished, it is useful to consider the subsistence farm situation in historical perspective.

In some of the poorer countries of Africa, for example, agricultural work is, for the most part, carried out by hand labor; tools are often simple and inefficient; corn is usually pounded (instead of ground) into a coarse flour, and used as the staple food. These agricultural methods were common to the Eastern Mediterranean Civilizations which flourished four to five thousand years ago (see Section 1.2.3). In the introduction to this thesis the extremely slow pace of the natural evolution of technology in agriculture was emphasized. But today, national and international pressures on the poorer agricultural nations demand higher productivity and efficiency in the agricultural sector of their economies and in this context, subsistence farming methods are an anachronism. The people of these nations cannot wait for "natural" evolution to guide them towards a more developed way of life.

The necessity for agricultural development is intensified by the rates of urbanization in the less-developed countries. The desire of most agricultural workers is that, with luck and perhaps a little harder work, they or their children can somehow escape from the countryside to the towns and cities. This movement is not

only a problem in urban centers, with shanty towns and massive unemployment, but also presents a formidable problem to agriculture. The more adventuresome, and thus potentially progressive farmers, leave agriculture for the comfort and excitement of urban living, leaving the less progressive farmers to work the land. As long as agriculture remains a form of bondage and the subsistence farmer has no opportunity to better his way of life in rural communities, this drain on agriculture will continue (31).

2.1.2 The Development Goal

In the broadest context, for those who believe that greater socio-economic equality will bring greater global stability by reducing the population growth rate and the incidence of war, development of the less-fortunate nations must be a priority. Development, as viewed by Peter Dorner, must reduce unemployment and underemployment and result in greater equality of resource distribution as well as increased agricultural production and productivity (8). The realization that employment and production must be viewed alongside economics suggests that "total development" is more than just a matter of "economic development". The goal in less-developed agriculture must therefore be to employ more people more effectively towards a greater productivity. Thus, a prerequisite for development in the agricultural sector of less-developed countries is that farming must be attractive to those with the energy and ingenuity to institute what will amount to an agricul-

tural revolution*.

It must be emphasized, however, that if livelihood in agriculture is not rewarded in both social and economic terms, the effect of even the most generous capital inputs and the most appropriate technologies will be undermined. Education oriented towards agriculture and the participation of the elites in agriculture is essential. As reported by UNESCO, in America only 4 percent of the many students that come from overseas for further academic training are interested in the fundamental problems of agriculture in their homelands (37). This illustrates very well the low esteem that is held for agriculture by the educated of the less-developed world.

2.2 POWER IN AGRICULTURE

2.2.1 Introduction of Power to Less-Developed Agriculture

The introduction of mechanical power to less-developed agriculture is an extremely controversial subject. There are those that suggest that the introduction of "labor-saving" devices will increase unemployment and is thus anti-development, while others reason that without the use of power machinery productivity cannot be increased appreciably (18). Actually, a compromise between the so-

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*The writer is not referring here specifically to a repetition of the agricultural revolution of the North Atlantic Region but of any process of change from anachronistic to appropriate agricultural methods.

cial and economic effects of power mechanization is required and local factors such as labor-availability and capital-requirements, etc., should determine an appropriate level of mechanization for each case.

One major effect of introducing power to the farm is to generate new interest in agriculture. When it is shown that agriculture need not be synonymous with back-breaking toil, hopefully, the more progressive farmers and their offspring will not be so eager to abandon the country for the town. However, in order to be compatible with "total development", it is essential that the introduction of power machinery does not displace many farm workers and is in some manner controlled by the farmers themselves*.

The small size of most farms in the less-developed countries means that if control is to be local* then the power source must, of economic necessity, be small-scale.

Therefore, the purpose of introducing mechanical power to the private agricultural sector of less-developed nations must be to: (a) free the farmer and his family

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*This matter of control is most important as it is control of the power source, not the power itself, that will give the farmer not only the ability to produce more but the incentive for him and his family to remain on the farm. This thesis is concerned with the development of the independent farmer, in preference to the reorganization of agriculture into large-scale farms, in the belief that progressive farmers will operate more efficiently on their own than when forced to work on large corporate farms.

from the drudgery of non-productive tasks such as water-carrying and flour-milling, in order that more time and energy may be spent on the cultivation of crops; (b) generate interest in agriculture and incentive for the progressive farmer to stay on the land; (c) provide inspiration for innovation necessary for increased agricultural productivity.

2.2.2 Power Alternatives

Three sources of power other than muscle power can be made available for use in less-developed agriculture: heat-engine power, waterpower and windpower*.

If the power source need be portable, then at present, the only alternative is the heat-engine of the internal combustion type. Internal combustion engine power is versatile, portable and dependable, all characteristics important for use in modern agriculture; however, its appropriateness for use in less-developed agriculture is debatable. Such power sources clearly require considerable capital resources for purchase and maintenance, as well as resulting in severe rural unemployment when put to large-scale use. This is clearly anti-development.

Natural power, derived from the energy of air and water motion, is limited to stationary use. In agriculture, both of these natural power sources have been

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*Any of these may be used to generate electric power.

used for centuries and the choice of which of these is to be used depends greatly on availability. In the rural areas of the less-developed countries where water is abundant, agriculture is already well developed. It is those areas that do not have an abundant water supply that are in greatest need and it is here that the use of windpower can have its greatest beneficial effect.

2.3 APPROPRIATE TECHNOLOGY

2.3.1 Definition

In the less-developed countries, the two extremes of agricultural mechanization have given similar results. The introduction of highly mechanized agricultural methods has often resulted in failure* and traditional agriculture, using minimal mechanization, has proven stable only at subsistence levels of production. Without some form of mechanization, the traditional farmer has little chance to improve his productivity to the extent required for stable development to occur.

Somewhere between these two extremes, it is concluded, there exists an appropriate level of mechanization that would better meet the needs of a less-developed agricultural country (31). A growing realization of the inap-

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*Not only does this approach fail to meet the goals of "total development", but the lack of supportive infrastructure such as spare parts supply or trained personnel often causes the physical failure and consequent abandonment of such highly mechanized projects.

propriateness of technology transferred directly from technically more advanced nations has given rise to the concept of "appropriate technology" for agricultural development (32).

The basic difficulty in direct transfer of technology developed in an industrial country is its capital-intensive, labor-saving premise. In less-developed countries, technology that will increase employment and reduce capital requirements is needed; that is, a capital-saving, labor-intensive technology. For example: a number of small, hand-powered flour mills may be preferable to one large electric or diesel powered mill.

Thus in 1965 the Intermediate Technology Development Group* was established in London to: (a) compile inventories of existing technologies, (b) identify gaps between existing technologies, (c) develop more appropriate technologies, (d) test and demonstrate results in the field, (e) publish results to facilitate the transfer and use of appropriate technology. It is hoped that the application of appropriate technology to problems of productivity in the less-developed countries will give better results than has the direct transfer of highly sophisticated western technology, advocated in the past as a shortcut to development.

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*Headquarters at Parnell House, 25 Wilton Road, London, England.

2.3.2 Relevance to Power

Applying the principles of appropriate technology to the production of power in less-developed agriculture leads to interesting results. For example, most large-scale, sophisticated power production machinery needs to be scaled down and simplified in order to be more appropriate. Similarly, full-scale tractorization is clearly inappropriate as it is indeed labor-saving and capital-intensive in the extreme* (32).

In a country where both trained personnel and capital are scarce, the use of such machinery causes considerable economic strain. With internal combustion engines the full economic impact is often not felt until the machinery has been in operation for some time. The need for fuel which must be purchased with scarce foreign exchange and the tying up of trained personnel to perform continuous maintenance are two factors that make its use for stationary power production most inappropriate in less-developed agriculture.

2.3.3 Appropriate Windpower Use

Although windpower is generally inappropriate for industrial applications**, windpower can be used in agri-

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*Yet many less-developed countries are still advocating large-scale tractorization (often in pursuit of prestige, not productivity). Research is presently under way at the National College of Agricultural Engineering in England to develop small-scale tractor technology specifically for use in less-developed agriculture.

**One exception is discussed in (45).

culture for those tasks which may be done *in situ*. Principally this includes water pumping and post harvest mechanization, both generally carried out by the women of rural communities. If windpower were employed to replace manpower in this case, its major effect on the labor economy would be to free those women to spend more time and energy on the more productive occupation of crop cultivation. This would be of direct advantage to those working the land and could do much to insure the success of such an innovation. According to M. Mamdani,

> Only under certain social conditions--that is, only when the adoption of a particular technology was in their interest--were the people responsive to technological change.
>
> (22, p. 52)

As with all innovation, the appropriateness of windpower will depend greatly on its form. At present there are a number of large-scale, sophisticated windpower projects underway but their capital-intensive, labor-saving character is not compatible with the needs of less-developed countries. Small-scale, simple windpower plants would be more appropriate. Their use would allow each farm or small village to have its own windpower plant which would minimize travelling distances, employ local personnel and give control of this "new" power source to the people who can make the best use of it. Another advantage of this type of small-scale installation is its educative effect upon the people that it serves. Through continual exposure to the advantages of innovation on the farm, tra-

ditionally "conservative" farmers may become "progressive" farmers and thus the process of development furthered.

2.4 WINDPOWER FOR AGRICULTURAL DEVELOPMENT

2.4.1 Advantages of Windpower

For stationary use, windpower has one major advantage over internal combustion power: wind is its fuel. Although this represents a considerable saving, the inherent costs of windpower (amortization, interest and maintenance) may or may not give it an economic advantage over fueled engines.

High operating costs, spare parts requirements and the need for continuous maintenance by trained personnel make the heat engines far from ideal for use in less-developed agriculture. On the other hand, natural power sources such as wind and water need not demand high operating expenditures and sophisticated maintenance inputs, but initial capital cost of natural power installations have traditionally been higher than that required for comparable heat engine power. Still, recent increases in the cost of petroleum products as well as recent concern over the environmental effects of combustion engine exhaust has done much to reduce heat engine competitiveness with natural power sources and this trend is expected to continue.

Water power is in many ways an ideal source of power for both developed and less-developed countries but it has one major disadvantage in the less-developed world.

Often flowing water is not available nearby and extensive electrification systems have yet to be developed sufficiently to provide hydroelectric power to the small farms of the less-developed countries.

2.4.2 Windpower Limitations

The greatest limitation of windpower use is the wind itself. Winds must be of sufficient quantity and quality to support windpower development for any given location. Quantity in terms of wind speed and quality in terms of wind speed variation must both be known before recommendations relative to windpower suitability can be made. Limitations on the size and complexity of windpower plants are usually governed by social and economic factors. (Using the appropriate technology approach, small-scale, simple windpower application is best suited for use in rural communities of less-developed countries.) Mechanical windpower plants such as those designed specifically to pump water or mill grain are also limited in their use and usually can only be used to do the one task for which each was built. By contrast, electrical windpower plants (or aerogenerators, as they are commonly called) are not as limited in their application and may be used for many tasks including lighting, water pumping, milling, etc. The use of an aerogenerator instead of a mechanical windpower plant also has the advantage that many tasks may be done simultaneously.

2.4.3 Economics of Windpower

The major expense associated with windpower utilization is the capital cost of construction and installation, and the corresponding interest charges. Operation costs are limited to periodic inspection and maintenance as, unlike the heat engines, there is no fuel requirement.

In order to measure the cost per unit energy, the following facts must be known: C, the capital cost of the windpower installation per unit of power capacity; p, the percentage applied in the calculation of the annual costs of interest, depreciation and maintenance; and E, the annual output of energy per unit of power capacity (called "specific output").

The calculation of energy cost is then simply: $(p \cdot C)/(100 \cdot E)$ per unit energy output. For example if capital cost is $1,000 per kw, annual charges are 20%, and specific output is 2,000 kwh per kw, then: energy cost, G, is $(20 \times 1000)/(100 \times 2000) = \$0.10$ per kwh.

The potential of windpower as a method of producing energy in competition with other methods is judged by comparing the energy cost, calculated in this way, with that for other alternatives. The capital cost, C, and the maintenance and depreciation components of the annual percent charges, p, depend largely on the design of the windpower plant itself. By using better materials, for example, C may increase but p should decrease and the overall effect on the cost of energy, G, can be calcu-

lated. In this way an economic design is produced.

The rate of interest charged on capital is determined largely by economic conditions in the country of purchase and the specific output, E, depends on annual wind speeds and the efficiency of energy conversion. Under normal conditions the cost of energy from the wind varies from 5 to 25 cents per kwh for typical plants presently in operation.

It must be pointed out, however, that economics, though an important factor, is not the only factor that must be considered in the application of power to less-developed agriculture.

2.4.4 Windpower Applications

A major use of windpower on the farm is for pumping water. On farms where water has to be drawn and/or transported by hand, it must be used sparingly. Often water scarcity prevents the raising of farm animals, and lack of sufficient water for even minimal irrigation leaves the farmer totally at the mercy of natural rainfall.

In some areas of the less-developed world, windpower could do much to increase the availability of water for small farms in remote areas and, with the addition of reservoirs, water could even be made available during periods of calm.

The use of windpower for direct water pumping has limitations in that the use of mechanical drive dic-

tates that the plant must be located very near (often directly above) the well, and this is often inconvenient. In addition, the direct connection between the windwheel and the pump gives the user little opportunity to vary loading conditions in order to maximize energy utilization. Energy that cannot be used immediately by the pump is thus wasted.

Other mechanical-drive plants similar to the wind pump may be used for post-harvest mechanization (thrashing, winnowing or milling), but mechanical energy is not easily stored and matching power availability to power requirement is often a problem. An alternate method of windpower utilization is offered by the wind-electric system.

From the 1920's through the 1940's, a number of small wind-electric plants were built in Europe and America producing electrical energy at 6 to 32 volts. In the days before rural electrification they provided an important source of energy to charge automobile batteries and provide electric light on the farm. Now, throughout the developed world, almost all of these small wind-electric plants have been replaced by more reliable power sources. In the rural areas of less-developed countries, reliable power sources such as those provided by rural electrification will not be available to the farmer for some time to come and there is a need to provide some means of energy production on the farm.

A major advantage of the wind-electric system

is its versatility. Electric power can be transmitted, by wire, some distance from its source*--thus eliminating the need for the power supply and power user to be adjacent. Electric energy may be stored in batteries to provide power during periods of calm. Electric appliances such as lights can be powered as well as machinery driven by electric motors. The versatility of electric power offers many advantages over mechanical power and provides a great deal more opportunity for innovation.

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*A small amount of energy is lost to heat due to the electrical resistance of the wire.

3. WINDPOWER THEORY

3.1 WIND

3.1.1 The Nature of Wind

Wind is air movement resulting from atmospheric pressure differentials. Four factors need be known to completely describe the wind at a particular time and location: its direction, its change in direction, its speed and its change in speed. For windpower use: wind direction may determine windwheel orientation, wind speed will determine available windpower, change in wind direction will determine windwheel orientation response, and change in wind speed will determine the variability of windpower output.

Three types of winds are recognized: prevailing winds, energy winds and storm winds. The prevailing winds are those which blow most often and thus determine the usual orientation of the windwheel. The energy winds are those that possess the greatest kinetic energy and are important in determining long range energy output of a windpower plant. Storm winds are those that have the greatest wind speed and are important in determining what forces the windpower plant must be able to withstand during storms.

A macroscopic view of the earth's prevailing winds suggests that the less-developed areas located near the equator are in the doldrums, and thus have little windpower potential (see Figure 1). This is most misleading as, although "average" wind speeds over large areas are low, local conditions are often such as to produce winds favorable to windpower utilization. Many areas within India, China, Africa and Latin America are at present using some form of windpower in agriculture although they are in the doldrums.

3.1.2 Power from the Wind

The amount of power available in the wind depends on its kinetic energy, E_k, such that:

$$P = \frac{E_k}{t} \quad \text{. . . . . (A)}$$

where: P is available power in kw,

E_k is the kinetic energy in kwh, and

t is the time period of energy extraction in hours.

Kinetic energy is defined as the energy of motion and:

$$E_k = \tfrac{1}{2}ms^2(2.78 \times 10^{-7})^* \quad \text{. . . . . (B)}$$

---

*Note that 1 Joule = 2.78×10^{-7} kwh.

where: m is the mass of flow in kgs. and

s is the flow speed in metres per second.

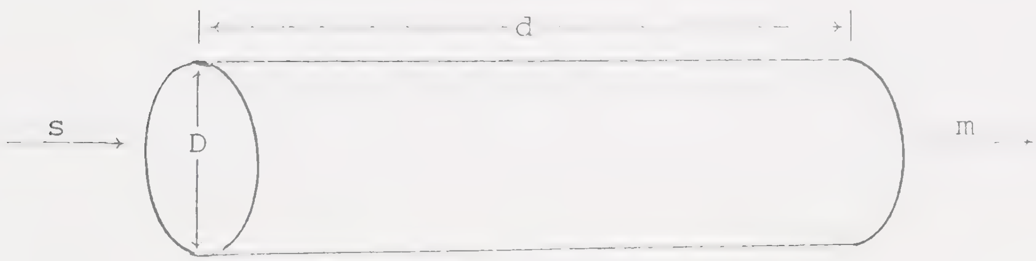
For a circular cross-sectional area perpendicular to the wind velocity, the mass of air, m, which flows through this area is given by: (see sketch below)

$$m = V \cdot f \quad . . . . \quad (C)$$

where: V is the flow volume in metres^3 and

f is the air density in kg./metres^3.

At 15°C, 60%R.H. and 100 mb pressure, f = 1.20 kg./metres^3



But: $$V = \frac{\pi \ D^2 \cdot d}{4} \quad . . . . \quad (D)$$

where: D is the cross-sectional diameter in metres and

d is the travel length of the cylinder of air in metres which passes through the cross-sectional area in time, t.

From (C) and (D) $$m = \frac{\pi \ D^2 \cdot d}{4} \cdot f \quad . . . . \quad (E)$$

From (B) and (E)

$$E_k = \tfrac{1}{2} \cdot \frac{\pi \ D^2 \cdot d}{4} \cdot f \cdot s^2 (2.78 \times 10^{-7}) \quad . \ . \ . \ . \ . \ (F)$$

From (A) and (F)

$$P = \frac{\tfrac{1}{2} \ \frac{\pi \ D^2 \cdot d}{4} \cdot f \cdot s^2 (2.78 \times 10^{-7})}{t} \quad . \ . \ . \ . \ . \ . \ (G)$$

But:

$$\frac{d}{t} = 3600 \ s \ ^{*} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ (H)$$

And:

$$f = 1.20 \ \text{kg./metres}^3$$

Therefore:

$$P = \frac{\pi (3600)(1.20)(2.78 \times 10^{-7})}{2 \ (4)} D^2 s^3$$

Or:

$$P = 4.71 \times 10^{-4} \ D^2 s^3 \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ (I)$$

From aerodynamic considerations, the maximum extractable power, P_o is given by:

$$P_o = 0.593P \ ^{**} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ (J)$$

The power coefficient, C_p, is defined as the ratio of actual power extracted, P_e, to the extractable power, P_o, and is thus a measure of energy conversion efficiency:

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*Note that t is in hours and s is in metres per second, hence the need for the 3600 conversion factor.

**In order that the air entering the plane of the windwheel be allowed to leave, it must retain some of its initial speed, thus only a portion of the total kinetic energy of the wind is "extractable". See reference (14) for detailed explanation.

$$C_p = \frac{P_e}{P_o} \quad \ldots\ldots\ldots\ldots \quad (K)$$

From (I) and (J) $P_o = 2.79 \times 10^{-4}\ D^2 s^3 \quad \ldots\ldots\ldots \quad (L)$

From (K) and (L)

$$P_e = 2.79 \times 10^{-4}\ C_p\ D^2 s^3 \quad \ldots\ldots\ldots \quad (M)$$

Even with the most modern windpower plants, a C_p value of 0.7 is seldom exceeded. Combining this with Equation (J) gives the result that only about 40% (0.7 x 0.593 = 0.415) of the kinetic energy of the wind can be usefully employed even under the most ideal conditions. For modern wind power plants a 30% energy conversion efficiency is considered excellent.

It should be emphasized that a major difference exists between energy extraction from a kinetic energy source such as the wind, and energy extraction from a potential energy source such as water. Potential energy such as that available in dams feeding hydro-power plants can be easily stored, but the kinetic energy of the wind must be used or transformed into other forms of energy, as it is supplied. It cannot be stored as kinetic energy for future use.

3.1.3 Choosing a Windpower Site

Both wind quantity and wind quality need be considered in choosing a windpower site. It is generally accepted that average windspeeds of less than 4.5 metres

per second are unsuitable for windpower, but wind quality is also a consideration. The steadier the wind, the more usefully it may be employed. Areas where long periods of high winds are followed by long periods of calm or where wind speeds characteristically vary greatly over even shorter time periods are less than ideal.

Generally speaking, wind speeds for most areas are entirely random (even though the averages and extremes may not vary greatly from year to year), so that even diurnal variation is not predictable (15). In order to best utilize what wind is available, the following generalizations should be noted: (a) wind speed generally increases with altitude so that it is often advisable to site a windpower plant on a hill if possible; (b) obstructions such as buildings or trees should not be within 400 metres of the plant, to reduce eddies and thus help to stabilize wind speeds; (c) in the tropics, winds are often greater at the coast than inland.

Ideally, so that windpower plant performance may be predicted with some accuracy before installation, at least one year's continuous record of wind speeds should be available from near the proposed site. The record can then be converted to power units using Equations (I), (J) and (K) of section 3.1.2 and accurate determinations of annual energy available, energy storage requirement and optimum power plant size may be made.

3.2 WINDWHEELS

3.2.1 Description

The windwheel (sometimes referred to as the "rotor") is the prime mover of the windpower plant. Its function is to convert the kinetic energy of the wind to mechanical kinetic energy which may then be used to do work. The windwheel itself usually consists of a number of radial blades, fixed to a central hub, which rotate an axle in response to the force of the wind. Power generated by the windwheel is then transmitted via the axle, directly or indirectly, to a mechanical or electrical system that can utilize or store the energy thus produced.

The efficiency of the windwheel is a major factor in overall windpower plant efficiency and thus its design is important.

3.2.2 Types of Windwheels

Windwheels are classed according to their plane of rotation and thus are usually termed "vertical" or "horizontal" axis windwheels. The most familiar type, like the American windpump or the Dutch windmill, are in the horizontal axis class. The earliest types, such as the ones first developed in Persia and China (see Section 1.2.7), are in the vertical axis class, as are a number of recent models presently under test by the National Research Council of Canada.

The advantage of the vertical axis windwheel is

that it accepts wind equally well from any direction without having to change orientation. The horizontal axis windwheel, on the other hand, must respond to wind direction in order that its plane of rotation be kept perpendicular to the wind velocity.

There are literally hundreds of types of each class of windwheel* but generally the horizontal axis design is more economical and efficient. As well, the inherent low-speed of conventional vertical axis windwheels make them quite unsuitable for aerogenerator use unless considerable speed reduction machinery is added. However, horizontal axis windwheels, depending on design, may be low or high speed. An example of the low-speed, high-torque horizontal axis windwheel is that familiar model used as a windpump in North America, wherein almost all of the swept area is filled by the windwheel blades. An example of the high-speed, low-torque horizontal axis windwheel is the propeller-type aerogenerator wherein only a fraction of the swept area is filled by the blades. (This type of windwheel has the greatest efficiency of all.)

Windwheel size varies from the small, two-metre diameter, commonly used on small farms, to the fifty-metre diameter wheel recently developed to produce electric power for utility companies in Europe and America.

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*See references: (1, 3, 10, 17, 24, 25, 30, 41, 44, 46).

3.2.3 Windwheel Selection

In selecting a windwheel for a specific application, torque and rotational speed must both be taken into account for a given power requirement. Type of windwheel to be specified is easily determined. For mechanically driven machinery, such as pumps, mills, etc., windwheel characteristics must be such as to provide a high starting torque and relatively low rotational speed at "normal" wind speeds. For aerogenerator use, windwheels should be of the high-speed propeller type.

Once the type of windwheel to be used for a specific application has been determined, an approximate value for its power coefficient, C_p, may be assumed and thus an appropriate windwheel diameter chosen [using Equation (I) Section 3.1.2]. Note, from Equation (I), that the power output varies with the square of the diameter, such that a doubling of windwheel diameter will result in a four-fold power output increase.

Rotational speed and torque are related to power by the following equation:

$$P = 2\pi\,\tau\cdot n(1.67 \times 10^{-5})\ * \qquad \ldots\ldots\ (N)$$

$$P = 1.04 \times 10^{-4}\tau\cdot n$$

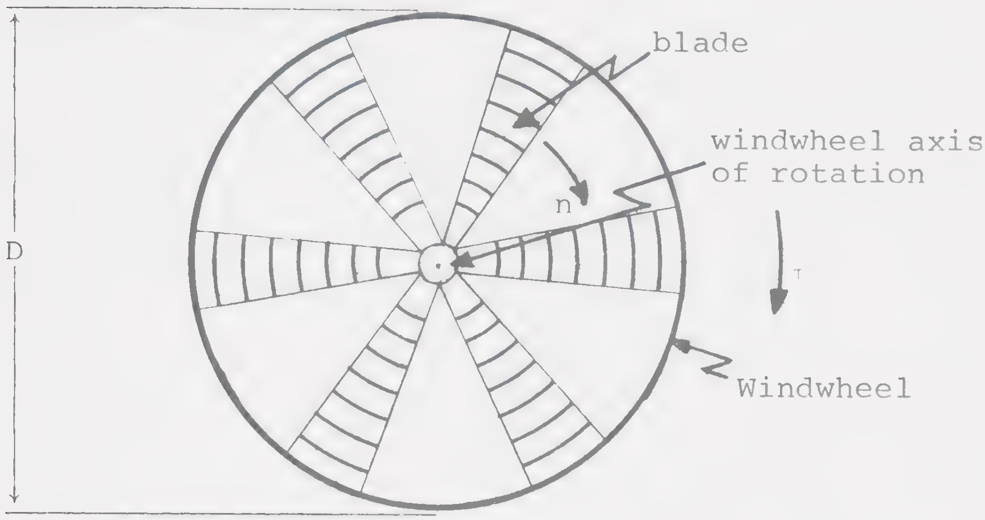
---

*Note that 1 newton-metre/minute = 1 Joule/minute = 1.67 x 10^{-5} kw.

where: P is the power output in kw,

τ is the torque in newton-metres and

n is the rotational speed in r.p.m.



Equation (N) illustrates that torque varies inversely with rotational speed such that, for a given power output, P, rotational speed, n, can be increased only by reducing torque, τ. This relationship governs the matching of windwheel characteristics to their application.

3.3 WINDPOWER UTILIZATION

3.3.1 Mechanical Power

During its earliest development and until the 1890's (see Section 1.2.7) windpower in agriculture was used exclusively to provide power by mechanical means.

A major problem with mechanical windpower transmission is the drive train necessary to connect the windwheel to the driven machinery. Drive train components, including gears, pulleys, driveshafts, cranks and levers, result in energy losses which reduce overall plant effi-

ciency while adding much to the plant cost. In addition, even the simplest mechanical drive train requires considerable maintenance, including the use of some form of lubrication essential to reducing wear and energy losses.

The difficulty of transmitting power mechanically for long distances usually means that the power user must be located as close to the windwheel as possible, often just below the windwheel support tower, and for many applications this is most inconvenient. Mechanical drives are seldom used to do more than one task, as a connect and disconnect capability would require special, expensive machinery, as would arrangements designed to increase versatility by allowing more than one task to be done at one time.

As wind speed changes constantly and windpower output varies as the speed cubed [see Equation (I) - Section 3.1.2], it is most difficult, with mechanical windpower plants, to utilize power as it is produced. During the "age of windpower" in Europe, on windy days millers worked very hard for long hours, and then relaxed during periods of calm. Often this is not a convenient or practical solution to matching power supply to demand and better results can be accomplished if some form of energy storage is used. Unfortunately, mechanical kinetic energy cannot be easily or economically stored.

3.3.2 Electrical Power

With the development of electricity in the 1890's

came the idea of generating electrical power from the wind. At first, aerogenerators were most often driven via a speed reduction system capable of increasing rotational speed to an acceptable level, but such machinery, as did the mechanical drive train, increased maintenance requirements and plant cost. Not until the 1920's, with the introduction of the efficient, high-speed propeller, was direct drive of aerogenerators made possible.

Electrical power from the wind had many advantages over mechanical power. In the wind-electric plant the troublesome drive train of the mechanical plant is replaced by maintenance-free electrical wiring. As well, more than one task can be done at a time, using electrical power, by simple connections. In this way power supply can be more easily matched to demand. Adding storage batteries to the wind-electric system also results in a more steady energy supply than previously offered by mechanical power plants*, but this may add considerable cost to the wind-electric plant.

However, the greatest advantage of electric power is its versatility; it can be used for lighting, driving electric motors or powering a number of electrical appliances. The simplicity, efficiency and versatility of the wind-electric system make it far superior to the wind-

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*Surplus energy can be stored for use during periods when demand is greater than supply.

mechanical system for use on small farms.

3.3.3 Energy Storage

To provide energy during calms and to better utilize wind energy as it becomes available, some form of energy storage is needed. For many applications, long or even short periods of zero energy availability are unacceptable.

There are two methods of energy storage commonly associated with windpower. The first, and perhaps the simplest method, is used when water supply is one of the energy users. In this case a water storage tank can be provided above ground level such that the water level in the tank will increase when supply is greater than demand and decrease when demand is greater than supply and thus water availability is greatly improved. This method provides a buffer between supply and demand which can, if properly designed, provide a reliable supply of water from the rather unreliable energy of the wind.

The second method requires that the kinetic energy of the wind be converted to direct-current electrical energy which can then be stored in batteries. This method, unlike the first, results in a considerable energy "loss" of about 15%, associated with battery inefficiency.

A more versatile system, which has water supply as one of its functions, can use both of the above methods simultaneously but the cost of such a system is often not justified.

4. WINDPOWER PLANT DESIGN

4.1 DESIGN CONSIDERATIONS FOR LESS-DEVELOPED COUNTRIES

4.1.1 Economic Inputs

In order that the benefits of windpower be made available to the greatest number of people, windpower plants must be within the budgets of many small farmers in less-developed agriculture.* Thus, in the design of a windpower plant for these areas, low capital and maintenance costs must be a priority. As capital and maintenance costs increase rapidly with windpower plant size, economic restraints dictate that the plant must be small if it is to be purchased and maintained by individual farmers or small co-operatives. Capital costs may be reduced considerably if maximum use of less-expensive, mass-produced, already-available components can be made.

The economic "trade-off" between capital and maintenance costs is difficult to analyse at this point.

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*Of course the greater majority of farmers in less-developed countries could not afford even the most minimal capital expense but there are those who can--either using their own resources or through bank credit--and it is these farmers that will be the first to benefit.

The use of more expensive equipment having lower maintenance requirements may be more economic in the long run, but this will require long-range prototype testing. Thus, in this design, the high priority given economics was initially translated to mean the reduction of capital costs to a minimum. The physical testing of the prototype resulting from this design will better determine what maintenance is required and at that point design improvements to reduce maintenance costs may be more reasonably introduced.

The synthesis of both capital and maintenance costs will result in a cost per unit of energy figure (as described in Section 2.4.3) which will ultimately determine the economic feasibility of such small-scale windpower use in less-developed countries.

4.1.2 Manpower Inputs

In less-developed countries, trained, capable manpower is scarce and the introduction of innovations requiring considerable expertise for their installation and maintenance cannot be successful without placing further strain on that country's human resources. If an innovation can be introduced using only readily available unskilled or semi-skilled labor, then it has a much better chance for survival.

Ideally, a windpower plant designed for use in less-developed agriculture should be easily installed by

local people and require only minimal maintenance by skilled personnel. If routine maintenance can be carried out by the people who use the plant, then it is quite feasible that the plant may operate for long periods without the need for any skilled labor input. Thus, the design of the prototype is such as to minimize skilled manpower requirements so that local people may be used for both installation and routine maintenance.

4.1.3 Technology Inputs

Design of the prototype windpower plant will be carried out using the principles of appropriate technology (as discussed in Section 2.3). Thus, an attempt will be made to use technology which has already been at least partially introduced into the country. In this way, it is hoped that the technical support needed for such windpower plants to operate successfully for long periods, can come from within the country rather than without.

4.1.4 Output Requirements

Ultimately, the success or failure of a windpower plant depends on its ability to perform the tasks for which it was designed. In this instance, affordable energy in sufficient quantities to meet demand is the primary output requirement. To attain this goal a high overall plant efficiency will do much to utilize more of the wind's energy. In addition, a windpower plant designed for use in less-developed countries should be able to pro-

vide power which can be used for more than one purpose. One installation should have the potential to pump water, mill grain and power other agricultural appliances. Thus the prototype design will attempt to maximize both plant efficiency and versatility to meet these needs.

4.2 WIND-ELECTRIC PLANT CONSIDERATIONS

4.2.1 The Wind-Electric System

The wind-electric system consists of a head, a support, wiring, storage battery(s) and a control panel. The head is made up of a windwheel driving a direct-current generator mounted on one end of a freely-rotating horizontal cross-member which is kept parallel to the wind by a rudder mounted on the opposite end. The head is mounted atop a support structure, and electrical energy generated is transmitted to the control panel by wire. In order that electrical energy may be stored, a storage battery is located at the base of the support and connected electrically to the control panel. The control panel contains instrumentation to measure current and voltage as well as a voltage and current regulator, to protect electrical components (see Figure 2 for general layout of a simple wind-electric system). Note that the wind-electric plant is being suggested here as more suitable than the wind-mechanical plant for reasons stated in sections 3.3.2 and 4.1.4.

4.2.2 Utilizing Automotive-Electric Parts

When the concept of wind-electric power was

introduced to the farmers of the developed world, the more ingenious would often build their own wind-electric set from 6-volt automobile electrical parts instead of buying the more expensive factory-made type. The major difficulty with this was that the direct-current generators used in automobiles at that time were inefficient and required considerable maintenance for continuous operation. Now, automobile generators are far more efficient and require little maintenance, and it is reasonable to assume that if the idea of producing power from the wind using automobile parts was introduced to the more ingenious farmers of less-developed countries, they, too, could put this idea to good use. If there is sufficient wind, even a small plant has the capacity to pump water, provide electric light and power small agricultural appliances.

Using automobile electrical parts for windpower utilization has all the advantages discussed in Section 3.3.2 but avoids the disadvantage of requiring a highly specialized technology which may not be readily available. The expertise required for the maintenance and repair of automobile electrical systems is already available in less-developed countries and spare parts may be obtained from existing automobile spare part depots. This eliminates the need for elaborate training programs and special service centers that would most definitely be needed if specialized windpower equipment were to be used. By building a windpower plant using parts from the automobile electri-

cal system, not only is the cost of the installation reduced but also its versatility is increased. All automobile components compatible with the 12 volt electrical system become readily available for use in such a system. Lights of various sizes, electric motors and car radios may be obtained and put to use.

It is recognized that a small, low-voltage system will only be useful for small loads, but its introduction will allow rural families to enjoy some of the benefits of electric power and will offer numerous opportunities for innovation.

4.3 PROTOTYPE DESIGN

4.3.1 Generator Specification*

At present, almost all automobiles and trucks are equipped with a 12 volt, direct-current generator of the synchronous-wound, diode-rectified type, commonly called the alternator. This relatively new design has several advantages over the shunt-wound, direct-current generator that was prevalent before 1967. These include:

a) Higher efficiency. The alternator system requires only about 24 watts of energy to power its electric field while the generator system requires 60 watts or more.

b) Lower speed operation. The alternator system produces useful energy at 800 revolutions per minute where-

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*See Figures 3, 4 and 5 for bench test data on alternators and generators.

as the generator system must be driven at 1300 revolutions per minute before its energy production equals its consumption.

c) Greater power capacity. The alternator system can produce up to 630 watts of power (at 4000 rpm) while the equivalent generator can produce only 270 watts maximum (at 2500 rpm).

d) Greater overspeed capability. The alternator can be run safely at 10,000 rpm but the generator is limited to 5000 rpm operation.

d) Less weight and volume. The alternator weighs only 5 Kgs. and is only 14 cm. long and about 16 cm. in diameter. The generator weighs 10 Kgs. and is 30 cm. long and about 15 cm. in diameter.

f) Less maintenance required. The alternator uses slip rings in place of the split commutator used in generators. As the commutator causes rapid brush wear, generators require frequent cleaning, inspection and maintenance.

For the above reasons it is suggested that the alternator, which is now readily available throughout the world, would be a much better source of electric power than the D.C. generator, and thus the alternator was used in the construction of the windpower prototype.

4.3.2 Windwheel Design

As mentioned previously in Section 3.2.3, the type of windwheel specified for a particular application depends largely on what rotational speed is required. In

this case it is desirable (in order to eliminate the need for a speed reduction system) for the windwheel to direct-drive the alternator. At rotational speeds of at least 1000 rpm a propeller type windwheel is needed.

As the propeller should be easily constructed and balanced, a simple two-bladed propeller (which has the added advantage of lighter weight) was specified.* The major limitation on the use of the two-bladed propeller is that diameters of 3 metres and greater have a tendency to vibrate excessively and for these cases a three-bladed propeller is usually recommended. As this windwheel was to be of much smaller size, a two-bladed propeller was not expected to have serious vibration problems.

Although metal propellers (usually made from aluminum alloys) may be stronger, lighter and have a longer life, their high initial cost and the fact that they could most likely not be produced economically in a developing country, make them unsuitable for this application. It is more appropriate to make the propeller of wood which is available in most areas and can be fashioned by local craftsmen. Both hard or soft woods can be used, and protection from the elements afforded by the use of common linseed oil. For this research, carefully selected eastern birch was used for the prototype propeller.

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*See Figure 6 for efficiency data for different blade configurations.

Propeller diameter determines power output for a given wind speed, and for the design condition of 1000 rpm from a 6 metre per second wind*. At this speed, a power output from the alternator would be about 105 watts (from Figure 5). If an alternator efficiency of 70% is assumed, the energy input to the alternator must be 105/0.7 or 150 watts. From Equation (M), Section 3.1.1, and by assuming a C_p value of 0.7, the required propeller diameter may be calculated:

$$P_e = 2.79 \times 10^{-4} C_p \cdot D^2 \cdot s^3 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (M)$$

where: P_e = the windwheel power output
= 0.150 kw

C_p = the power coefficient
= 0.7 for propellers

D = the windwheel diameter (metres)

S = the windspeed
= 6.0 metres per second.

Solving for D in Equation (M):

$$D = \sqrt{\frac{P_e}{2.79 \times 10^{-4} C_p \cdot s^3}} = \sqrt{\frac{0.150}{2.79 \times 10^{-4} \times 0.7 \times 6^3}} \quad . \; . \quad (O)$$

$$= 1.9 \text{ metres}$$

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*This design figure is chosen from wind speed availability data and alternator rotational speed requirement.

As the area of the propeller near its center is not used for power production, a propeller of 2.00 metre diameter was specified.

The pitch of the propeller blade, that is, the angle between the blade surface facing the wind and the perpendicular to the wind direction, determines propeller characteristics. For a given wind speed, propeller torque increases and rotational speed decreases with increasing pitch and vice versa. However, in order that wind slip be kept constant along the blade length, pitch must decrease from blade root to tip. At a point 50 cm. from the propeller axis, the blade moves $2\pi \times 50$ cm. or 3.14 metres each revolution. If the propeller rotates at 1000 rpm, then this point must move 3140 metres per minute or 52.3 metres per second. As the propeller is to rotate at 1000 rpm in a 6 metre per second wind, assuming a 30% slip of the blade with respect to the wind, the pitch ratio, P_r*, will be $52.3/(6 \times 0.7)$ or 12.5 and as the pitch angle, Φ, equals the cotangent inverse of the pitch ratio, $\Phi_{50} = 4.5°$. Similarly, at the blade tip, $P_{r100} = 25$ and $\Phi_{100} = 2.3°$. At the blade root, $P_{r10} = 2.5$ and $\Phi_{10} = 22°$.

According to Juul (27), the shape of the blade tip can greatly affect propeller efficiency (see Figure 7). The most efficient design is semicircular tips with

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*The pitch ratio, P_r, is defined as the cotangent of the pitch angle.

the downwind blade surface bevelled to a sharp point. In addition, extensive experimentation by J. Juul indicates that the most efficient propeller blade shape (profile) is as illustrated in Figure 8. Another advantage of this profile is that it can be approximated by four straight lines (as illustrated in Figure 9) greatly simplifying propeller construction. These design improvements were used in the construction of the prototype propeller.

In order that the propeller be fixed directly to the alternator, it was drilled as shown in Figures 10 and 11.

4.3.3 Head Design

The "head" of the wind-electric plant includes the windwheel mounted on the generator, the vane and the crossmemeber to which all these components are attached. The entire assembly is designed to rotate in a horizontal plane in response to the wind direction, such that the plane in which the windwheel (propeller) rotates is always kept perpendicular to the wind. In order that the windwheel be mounted on the alternator as simply as possible, the propeller was bolted directly to the alternator pulley assembly as shown in Figures 12 and 13. A bracket with which to fix the alternator to the crossmember can be easily constructed from pipe fittings and short lengths of steel water pipe, using the mounting lugs of the alternator as shown in Figure 12.

The most common and perhaps the simplest method

of "steering" the head is to attach a vane to the crossmember at the end opposite the alternator assembly in such a manner as to balance the head on the vertical tower axis. The sensitivity of the head to wind direction depends on the area of the vane and its moment arm measured from its axis of rotation. For a two-metre propeller mounted within thirty centimetres of the head axis of rotation, a vane surface area of about 1200 $cm.^2$ and a moment arm of about one metre is adequate (24). The vane was attached to the crossmember by cutting a vertical slot in the crossmember and bolting the vane in place (see Figures 14 and 15). Note that the vane was streamlined to reduce turbulence and was made of galvanized sheet stiff enough to avoid non-elastic deformation by the wind. For this reason 16 gauge material was specified.

In order that the head be allowed to rotate freely in a horizontal plane about the vertical tower axis, a number of methods can be employed. The simplest acceptable method is to use a steel pipe, "T" fitting as the bearing surface on the pipe circle of the uppermost tower section. For support, the "T" fitting was screwed onto a length of pipe of sufficient diameter so as to fit securely inside the uppermost tower section to serve as the head assembly axle as illustrated in Figure 14. In this instance the construction of head structural members was carried out using common 3/4 inch steel water pipe and fittings.

4.3.4 Tower Design

Ideally the tower should be designed to:

a) support the head and not be damaged by high winds;

b) utilize materials available in less-developed countries and require little expertise to assemble;

c) allow for maintenance of head components without requiring that the tower be ascended;

d) be relatively inexpensive to purchase and maintain;

e) be high enough to avoid ground interference with the wind; and

f) be sectional for ease of portability.

The most common type of tower for use with small-scale windpower plants is the rigid frame, but it has one disadvantage in that the tower must be ascended each time the head assembly requires inspection or maintenance. One alternative is to design the tower such that it can be rotated about a pivot near ground level and thus be brought within easy reach. This design also has the advantage that the entire tower may be lowered in the event of an impending violent storm and thus be protected from destruction. In order that the tower may be raised or lowered easily by one man, a counterweight may be used.

The design height of the tower depends largely on how the wind is affected by nearness to the ground and to other possible interferences such as trees and buildings. For this application a 10.0 metre design height

was specified.

The tower itself was constructed entirely of common sizes of steel water piping and used screwed connectors and flanges for ease of assembly. Five sections of 1.80 metre length were used for the erect portion of the tower and one additional 1.80 metre length used to support the counterweight. A "rest" to support the tower in the lowered position was attached to the main tower and one additional support was used for wind-sensing instrumentation. A design wind speed maximum of 20 metres per second (45 mph) was assumed.

The horizontal force exerted against the wind-wheel during a 20 metre per second wind can be calculated from:

$$T = 2\pi r^2 fV^2 a(1-a)^* \quad . . . . \quad (P)$$

Substituting,

$$T = 2\pi(1.0)^2(1.2)(.12)(1 - .12)V^2$$

$$T = 0.80V^2 {}^{**} \quad . . . . \quad (Q)$$

When V is 20 metres/second,

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*See (11).

**See Figure 16 for a plot of this function.

$T = 320$ newtons

where: T = thrust force in newtons

r = propeller radius
= 1.00 metre

f = density of air
= 1.20 Kilograms/metre^3

V = windspeed
= 20 metres/second

a = interference factor*
= 0.12

As the tower was designed for a maximum wind speed of 20 metres/second, pipe sizes to be used to make up the tower could be specified. Stress analysis of the tower was carried out in tabular form (see Figure 17) and the resulting tower illustrated in Figure 19. From stress analysis it is clear that stresses would not exceed the 41,500 newton/cm.^{2} tensile strength limit of steel pipe and thus tower failure should not occur at wind speeds less than 20 metres/second.**

In order to reduce the probability of raising or lowering the tower accidently, it is desirable that the tower be stable in both the vertical and horizontal positions (when allowed to rotate freely about the upper pivot). This demands that the counterweight (which is to help resist the moment caused by the weight of the tower

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*a = 0.12 when the propeller efficiency is about 40% (11).

**See reference (21) for steel strength data.

when in its lowered position) as illustrated in Figures 20 and 21, must be carefully specified. Calculation of a suitable weight was carried out in tabular form in Figure 22. The counterweight itself, which consists of a solid block of concrete cast about a 3.5 inch nominal diameter pipe section, is illustrated in Figures 23 and 24. Note that the moment applied to the tower when in its vertical position may be adjusted by securing the counterweight at any one of a number of positions along the length of the counterweight arm.

The fork (which was made up of two lengths of 2.5 inch nominal diameter pipe, flanged and bolted to a larger pipe flange) allows the tower to be raised and lowered by rotating the tower about a pin fitted through the fork at its upper end (see Figure 25). When the tower is erected, with the lower lock pin secured, the fork must be able to support the tower in a 20 metre/second wind. As with the tower design, the thrust force on the propeller, T, will be 320 newtons. At ground level, this force will cause a moment of (320 newtons)(10 metres) or 3200 N-m. The resulting maximum stress on each of the two fork pipes will be S_f, and,

$$S_f = \frac{M \cdot r_g}{I} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad ([illegible])$$

$$= \left(\frac{(3200)(0.036)}{2(0.476 \times 10^{-6})} \right) \left(\frac{N}{m^2} \right)$$

$$= 12.1 \times 10^7 \ N/m^2$$

$$S_f = 12{,}100 \ N/cm.^2$$

where: M = the maximum bending moment

$= \frac{3200}{2}$ N-m*

r_g = radius of gyration
$= 0.036$ m. (from Figure 17)

I = moment of inertia
$= 0.476 \times 10^{-6}$ metres^4
(from Figure 17)

As the allowable stress is 41,500 N/cm.^{2}, a fork support made from 2.5 inch nominal diameter pipe is adequate.

In order that the entire tower may be rotated on its base, the pipe flange, to which the fork support flanges are bolted, works as a turntable. The ability to rotate the tower in this manner is often useful as the wind can then be used to assist in the lowering or raising of the tower. A sleeve within which the turntable axle rotates and the bearing surface on which the turntable turns is illustrated in Figure 25.

The tower footing consists of a 1.8 metre length of 4 inch pipe, one end of which has been threaded and screwed into a standard 4 inch cast iron flange. (This

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*Each fork member supports half the load.

flange serves as the bearing surface for the turntable flange about and was specified as cast iron instead of steel as cast iron is a better bearing material.) The footing was installed simply by boring a suitable size hole in the ground and tamping the pipe securely in place as is done with fenceposts. The turntable assembly was then inserted into the footing pipe as shown in Figure 25.

Again the overturning moment must be considered. Assuming the footing rotates about a point at the bottom of the footing on failure of the soil (the worst possible condition), the overturning moment, M, would be the product of the thrust force, T, and the moment arm, H. Where h = 10.0 + 1.8 = 11.8 metres and T is 320 newtons. Assuming the resulting compression force on the soil, F_c, acts at a point half way up the footing,

$$F_c = \frac{320N(11.8m)}{0.9m} = 4200 \text{ newtons.}$$

The projected area of the footing, A_f, is 11.4 cm. x 180 cm. or 2060 cm.^{2}

Therefore, the soil compression stress, S_s, =

$$\frac{4200 \text{ N}}{2060 \text{ cm.}^2} = 2.0 \text{ N/cm.}^2$$

As soil compression strength is commonly in the order of

14 N/cm.^{2},* this footing will be secure in a 20 metre/second wind.

4.3.5 Electrical System Design**

The electrical system (as discussed previously in section 4.2.2) utilizes automotive electrical parts for its construction to perform the following tasks:

a) control alternator output;

b) prevent possible high-current damage to system;

c) indicate alternator output;

d) provide electrical energy storage for use during calms;

e) prevent complete draining of stored energy; and

f) automatically disconnect field current when wind is not sufficient to produce a new power output.

The alternator current and voltage output was controlled in the same manner as in the automotive electrical system. The voltage regulator used for this purpose was mounted inside a control box fixed to the tower fork support.

Shorting of a battery or alternator circuit could cause considerable damage. To insure that such an accident does not occur, fuses were used to limit current in

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*Most soils have an allowable compression rating of about 3000 lbs/ft.^{2} which is equivalent to 14.14 N/cm.^{2}.

**Note that generator specification was carried out separately in Section 4.3.1.

each of these circuits.

In order that the output of the plant could be monitored, automotive type gauges (one 0 to 15 volt voltmeter and one -60 to +60 ampere ammeter) were mounted on the control box.

Storage of electrical energy was made possible via two 12 volt, 115 amp-hr automotive batteries. Each battery was kept inside a metal storage box set on the ground near the base of the tower and connected to the control box via flexible cables.

Complete draining of the energy stored in the batteries is prevented by connecting one battery to the circuit through diodes taken from an old discarded alternator. These diodes are connected such that current is allowed to flow to the battery from the charging circuit but is not allowed to flow to the external load. This battery is thus reserved to supply energy to the alternator field only. Draining of this "field battery" is prevented by a wind-operated switch mounted near the vane at the top of the tower such that the alternator field is energized only when there is sufficient wind for net energy production.

In the prototype, transmission wires from the alternator to the control box at ground level pass through the center of the tower. Flexible wires with considerable slack are used such that rotation of the head will not

cause twisting sufficient to break the wires.* Under normal conditions wind direction seldom changes in such a manner as to rotate the head a full 360° but as a precaution it is advisable to prevent the head from rotating more than about ten revolutions in either direction. This can be done by simply attaching one end of an appropriate length of rope to the alternator support bracket and the other end to the upper tower section such that the rope becomes taut and prevents further head rotation beyond the ten revolution limit. If this limit is ever reached, the tower can be lowered and the head turned back again to the untwisted position.**

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*This idea is taken from reference (24).

**Hourly wind data from the Ellerslie Weather Station near the site indicates that during a 25 day period, the change in wind direction was such as to cause 4 clockwise and 1 anti-clockwise rotation of the head. This means a net twist of only 3 revolutions in 25 days. A 25 day period was chosen randomly for this consideration and data from September, 1972 was used.

5. EXPERIMENTAL PROCEDURE AND RESULTS

5.1 CONSTRUCTION

5.1.1 Choosing a Site

The prototype, as described in Section 4.3, was assembled for testing at the University of Alberta Ellerslie Farm. A site was chosen in an alfalfa field completely devoid of trees or other obstructions to the wind. Windward of the plant there were no obstructions to the wind for more than a kilometre and the terrain within 200 metres of the site was very flat.

As soil strength is important in supporting the tower footing, a soil test hole was bored to a depth of two metres. The top 60 centimetres of soil at the site was found to be a heavy clay loam. The soil from this depth to the two-metre mark was found to be primarily a heavy clay which is ideal for supporting the tower footing. (See Section 4.3.4 for details of footing.)

5.1.2 Tower Construction

A vertical hole was hand-bored to a depth of about 1.8 metres at the site chosen and the pipe footing set in. This pipe was then firmly tamped in place with its threaded end just above ground level and the footing

bearing flange screwed tightly in place. The tower axle complete with turntable flange was then inserted into the pipe footing and lowered into position. Next the fork support flanges were bolted securely to the turntable flange and the tower forks screwed into the fork support flanges such that the holes drilled for the tower lock pins were aligned.*

The main tower was assembled on the ground and the two insulated electric cables threaded through the tower by means of a long piece of tubing. The bottom of the tower was then fixed to the tower forks via the lower tower fork pin and the tower rest attached to support the top of the tower off the ground. Using a rope, the tower was then erected by rotating it about the lower tower lock pin until it was vertical and the holes through the upper end of the forks aligned with the hole in the tower. The tower pivot pin was then inserted to lock the tower in its upright position. The counterweight arm was screwed into position and the counterweight slid onto the arm and fixed into position by the counterweight lock pin (as shown in Figure 23). Then the tower lock pin was removed and the tower lowered by rope to its horizontal position as shown in Figure 24. In this position the head assembly was fixed to the upper tower section as shown in Figure 15 and the

*This operation is illustrated in Figure 25.

instrument support screwed in place.

5.1.3 Electrical System Assembly

With the tower still in the horizontal position, the two transmission wires were connected through suitable fuses and the wind switch to the alternator terminals. In addition, the alternator was grounded by wire to the tower head assembly frame.

The control box was assembled in the shop. It contains the voltage regulator, control switches, diode assembly and instruments required to control and monitor plant operations (see Figure 27 for details). A set of terminals at the bottom of the box facilitates external connections and the control box itself is grounded to the tower. The control box is fixed securely to one of the tower fork supports.

A simple wind sensitive switch was constructed using a common spring return toggle switch and a small piece of galvanized sheeting. Its function is to open the circuit between the field of the alternator and the field battery during calms so that the alternator field is not energized when the wind is not sufficient to produce net power. The switch is mounted to the upper edge of the vane and the galvanized sheet is fixed to the toggle such that it is perpendicular to the vane and pressure on the windward side will close the switch. The area and shape of this sheet, required to keep the switch open until wind speed became sufficient to produce net power, was deter-

mined by trial and error.*

The storage batteries were placed near the tower base and all suitable connections between the control box, transmission lines, batteries and the external load were made.** Details are shown in Figure 26.

5.1.4 Propeller construction

The first propeller was made from a solid piece of white pine measuring 2 metres long, 10 centimetres wide and 4 centimetres thick. The propeller hub was formed by cutting out a circular piece from its center sufficient so that the propeller fits over the alternator pulley and flat against the alternator cooling fan as shown in Figure 12. The propeller hub was then completed by drilling four holes (as shown in Figure 11) so that the propeller is bolted securely to the alternator. The exact center of rotation of the propeller was found by mounting and rotating the propeller.

To ensure accurate carving of the propeller, lines tangent to the circle of rotation are drawn on all faces at 10 centimetre intervals measured from the center. As the aerodynamic profile of the blade is well approximated

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*With the automotive toggle switch used, a sheet 15 cm. x 9 cm. with the longer side mounted vertically was sufficient.

**For use in tropical countries it is suggested that the batteries be installed in a pit at the base of the tower. This will reduce battery temperature which will do much to increase battery life.

by a series of four straight lines (see Figure 9), the intersection of these straight lines can be marked out. The propeller is then carved by fixing it securely in a bench vise and using a draw knife and block plane to remove excess wood. The transition points between successive straight lines approximating the blade profile were smoothed out using coarse grit sandpaper.

The blade tips were cut to circular shape and tapered on the back side as discussed in Section 4.3.2. The propeller was then placed on a knife edge at its center and balanced statically by removing wood with coarse grit sandpaper from the heavier side. Once balanced, all surfaces were sanded smooth with medium grit sandpaper and then polished with fine grit sandpaper. The propeller was then weather-proofed by coating liberally with boiled linseed oil and removing the excess with a dry cloth.

5.2 TESTING AND EVALUATION

5.2.1 Instrumentation

In order that the power output of the alternator could be measured directly during testing, a portable direct current power meter was used. A variable resistance load cell was used to simulate the effect of an external load on the system. To complement the voltmeter built into the control box, a hand-held voltmeter with a more sensitive scale was also used during testing.

As wind speed varies greatly over even very short

time intervals, it was decided to use a run-of-the-wind meter (which measures the distance the wind moves) in conjunction with a stop watch to measure average wind speed. This arrangement has the advantage that average wind speed could then be measured over any convenient time period. The windmeter was mounted parallel to the plane of propeller rotation at the top of the tower and out of the way of wind effects produced by the rotation of the propeller. Starting and stopping the meter was accomplished by a nylon control line run to ground level.

Propeller rotation speed was measured by a stroboscope both in the laboratory and in the field. In the field it was necessary to use a portable generator to power the stroboscope and to do testing only when it was sufficiently dark.*

5.2.2 The Support System

The support system was evaluated on the basis of the design criteria stated in Section 4.3.4. The tower supported the head in winds up to 14 metres per second but there was considerable deflection of the upper tower sections at this wind speed.

The tower was easily raised and lowered by one man even during high winds and the counterweight system

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*Rapid changes in propeller speed in the field made its measurement with the stroboscope impossible. As a result all propeller speed measurements had to be done in the laboratory.

proved most satisfactory. Although the tower was a full 10 metres in height the wind did not prove to be in the least constant. It was not ascertained how much of this variation was due to interference from the ground and how much was due to the nature of the wind itself.

The footing for the tower remained secure throughout the test period and the ability to rotate the tower freely on the turntable assembly proved most useful.

After completion of evaluation and testing it was decided to subject the prototype windpower plant to extreme wind speeds to note any plant defects that became apparent under storm conditions. The plant was set up during high winds of about 15 metres per second gusting to 20 metres per second.* Extreme deflection of the top section occurred. As the propeller came up to speed, tower deflection increased until the upper section sheared off at section d--d (see Figure 19) 6 metres from ground level.** The propeller was completely destroyed on contact with the ground.

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*These wind speed values were measured by nearby weather stations, not by wind instrumentation mounted on the tower.

**Failure of the tower occurred at the weakest section as expected from the stress analysis of the tower carried out in Figure 17.

5.2.3 The Electrical System

The performance of both the alternator used in the prototype and a comparable D.C. generator was investigated under controlled conditions at the Northern Alberta Institute of Technology in Edmonton (see Figures 3 and 4). Regulator controlled voltage and current output was measured at 250 rpm intervals from 0 to 5,000 rpm. Aside from the better performance of the alternator compared to that of the D.C. generator (see Figure 5) it is important to note that an alternator rotational speed of at least 1,000 rpm is required to produce useful power.

The electrical control and monitor system worked well throughout the test period but operation for many more hours would be required before the dependability or life of this sytem could be adequately determined.

5.2.4 The Propeller

In order to check propellers for dynamic balance in the laboratory, a D.C. motor powered by 12 volt batteries was mounted securely to a large concrete structural column. This provided for testing of propellers at speeds in excess of 1,000 rpm and gave some indication of their performance in the field. The first propeller was constructed from a single piece of white pine and proved to be stable only at speeds less than 900 rpm. At about 920 rpm this propeller vibrated excessively and further power to the driving motor only resulted in more violent vibration with no increase in rotational speed. All at-

tempts to balance this propeller by fixing weights to the blades proved fruitless. The same vibration would always occur at the same speed. This led to the conclusion that this vibration was not due to propeller imbalance but to flexing of the blades in the plane perpendicular to the plane of rotation.

To test this hypothesis a second propeller was constructed, again of white pine, and similar to the first except that the blade was made much thicker near the hub to increase its stiffness. Subsequent testing revealed the same problem that had been experienced with the first propeller. This time vibration occurred at about 950 rpm.

Before further work was to be done, some means of discovering whether vibration was occurring in the plane mentioned, or by some other mode, had to be devised. To this end a device was built to greatly increase blade stiffness.

A bracket was constructed to fit onto the propeller hub and to support a shaft which projected outward along the axis of propeller rotation. A fine stainless steel wire was then stretched from the tip of each blade to the tip of this shaft and tensioned such that blade stiffness would be greatly increased. This was done to the first propeller and when it was tested again, no vibration occurred even at the maximum motor speed of 1050 rpm. This led to the conclusion that greater propeller stiffness was required to eliminate vibration.

Stiffness could be increased in one of two ways. The first way would be to simply use the wire tension device already available, but as this would add considerably to the complexity of the plant, this solution was rejected. The second way way was to build yet another propeller out of wood with a much greater stiffness than white pine. As most woods commonly available in the tropics are hardwoods anyway, this was the logical solution.

A piece of eastern birch was fashioned into a third propeller. Subsequent testing of this propeller in the laboratory showed no vibration problem even at the maximum motor speed of 1050 rpm. This propeller was then mounted to the alternator in the field and field testing began.

5.2.5 Power Production

To measure power produced by the alternator, the power meter mentioned in Section 5.2.1 was connected to measure current flow from the alternator and voltage drop across the variable load cell. The load cell was set to give a voltage drop of about 12 volts and one 12 volt battery was connected to energize the alternator field. Average wind speeds were measured using the windmeter and stop watch described in Section 5.2.1.

In measuring power production of the windpower plant in the field, two major difficulties were encountered. The first problem was that wind speeds in the Edmonton area are not particularly high and therefore suit-

able wind speeds for testing were seldom available. The second problem is that during winds of sufficient speed, speed variation was so great that, even over short periods, accurate wind speed averages were difficult to obtain. As the power output of the plant varies with the cube of the wind speed [see Equation (I)], greatly variable wind speed resulted in even greater variation in power output. For example: a doubling of wind speed would result in a power output increase of eight times. As a result, it was most difficult to match power output to a specific wind speed. The most accurate power production figure was obtained during a relatively steady wind of about 11 metres per second. At this wind speed, 290 watts of power were produced.

5.2.6 Economics of Small-Scale Windpower

As discussed in Section 2.4.3, the economics of windpower are based on three factors: C, the capital cost per unit of power capacity; p, the percentage applied to the annual costs of interest, depreciation and maintenance; and E, the specific output.

The capital cost of the prototype plant which has been designed, built and tested is as follows:

Support System Cost	
Footing Materials	\$145.90
Main Tower	69.00
Counterweight Assembly	46.40
Subtotal	\$261.30

Power Production System Cost	
Head Assembly	$ 22.00
Electrical System	177.00
Subtotal	$199.00
Total Prototype Cost	$460.30

As only new materials were used for prototype construction,* this cost is considerably higher than would be expected if second-hand materials were used. It is interesting to note that the cost of the support system is considerably more than the cost of the power production system itself.

The maximum power capacity of the plant is assumed to be about 500 watts.** Therefore C will equal $460.30/500W or $921 per Kw capacity. Percent annual charges, p, are assumed to be about 20% and the specific output, E, will usually be about 1,000 Kwh per Kw. The cost of energy, G, can then be calculated from:

$$G = (p \cdot C)/(100 \cdot E) \qquad \text{(S)}$$

$$= (20 \times 921)/(100 \times 1{,}000)$$

$$= \$0.18 \text{ per Kwh}$$

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*With the exception of the alternator which was bought reconditioned.

**At the design maximum wind speed of 20 m/sec., a resultant propeller rotational speed of 2500 rpm would produce 500 watts of power (From Figure 5). This capacity is "assumed" as reliable test data at this wind speed was not obtained.

Although a number of assumptions have been made in this calculation, the result is indicative of the high cost of energy produced from the wind.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The major conclusion of this thesis is that it is feasible to design, construct and operate small-scale windpower plants for use in rural areas using only materials and expertise already available in less-developed countries. However, the cost of energy thus produced from the wind will depend heavily on the local cost of required materials. High material cost may result in energy from the wind being very expensive by North American standards.

In the rural areas of less-developed countries, petroleum fuels are expensive and hydropower is usually not yet available. It is here that windpower has its greatest potential. In a modern industrialized country, however, windpower will not be competitive with conventional petroleum power until the cost of fuel is far greater than it is today.* In addition it is also quite certain

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*The cost of energy produced by petroleum fueled engines is presently about \$0.07 per Kwh compared to \$0.02 per Kwh for hydroelectric energy compared to \$0.18 per Kwh estimated for the prototype windpower plant tested. It should be emphasized here that for many applications not only is the energy extracted from the wind expensive but its dependence on the availability of sufficient wind speed limits its use.

that windpower will never compete successfully with hydropower for reasons stated in Section 1.2.7.

6.2 RECOMMENDATIONS

6.2.1 Design Improvements

From the design, construction and testing of the prototype much was learned concerning the practical applications of windpower. From this experience a number of suggestions for further improvement of the prototype design may be made.

In an attempt to reduce capital costs, the footing design may be simplified considerably by eliminating the ability of the entire tower to be rotated about its vertical axis. This will reduce the footing cost by about $80.00.

The test to destruction that was carried out in high winds indicated that shortening of the tower would be beneficial in reducing the bending moments, caused by wind thrust on the propeller, thus adding to the safety and life of the plant. By constructing a tower six metres in height, instead of ten, a further capital cost saving of about $20.00 may be made. In addition, it is deemed unwise to subject screwed connectors to bending unless considerable factors of safety can be afforded. Thus the elimination of all screwed connectors in the main tower is recommended such that the main tower will consist of a continuous pipe length. This will result in further

savings of about $15.00.

These improvements to the design of the prototype will result in a simpler design and will reduce capital cost of one plant, by about $115.00 to $345.30. This saving will in turn reduce the expected cost of energy from the wind to about $0.14 per Kwh.

The counterweight system designed to allow for easy raising and lowering of the tower proved most satisfactory as did the electrical system. As the electrical system costs are mainly due to the cost of the batteries ($96.00 for two), electric wire ($20.00) and the alternator ($25.00), significant reduction in the electrical system cost would be difficult. Other simplifications to reduce capital costs are possible but are not advised as design priorities would have to be compromised.

6.2.2 Further Research

It is suggested that windpower has potential as a viable alternative power source for use in less-developed agriculture and could do much to further the development of the agricultural sector. To this end it is suggested that further research is warranted. Such research would be most useful if it were carried out in selected areas of the less-developed world with emphasis on using local materials and labor.* Both wind-electric

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*Similar to the work carried out by the Brace Institute in Canada but perhaps more consideration could be given to small-scale windpower.

and wind-mechanical plants should be given consideration but emphasis should be placed on small-scale plants as these will be accessible to the greatest number of people.

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Appendix 1

FIGURES

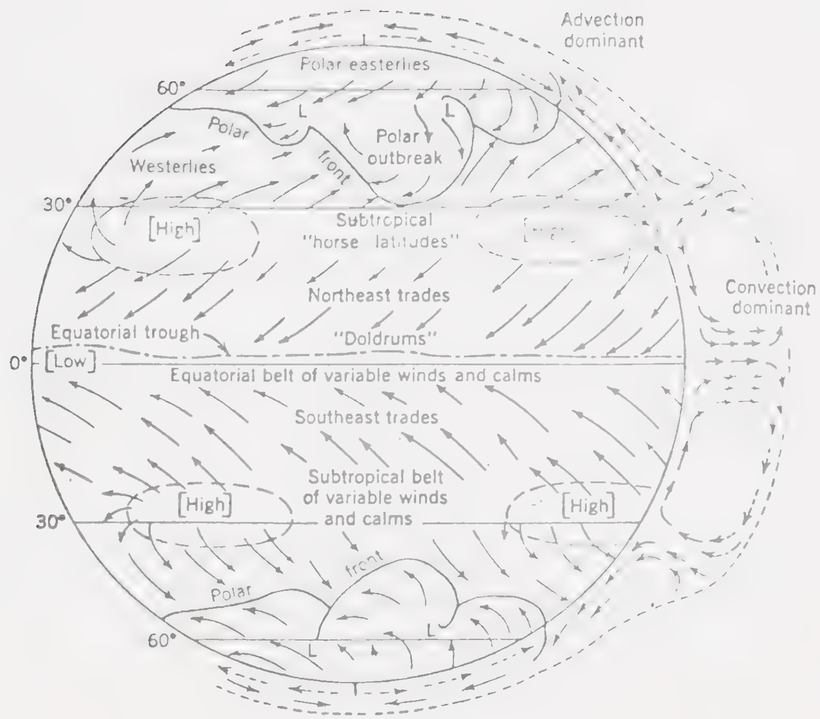

Figure 1* A Macroscopic View of Prevailing Winds

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*Taken from (36).

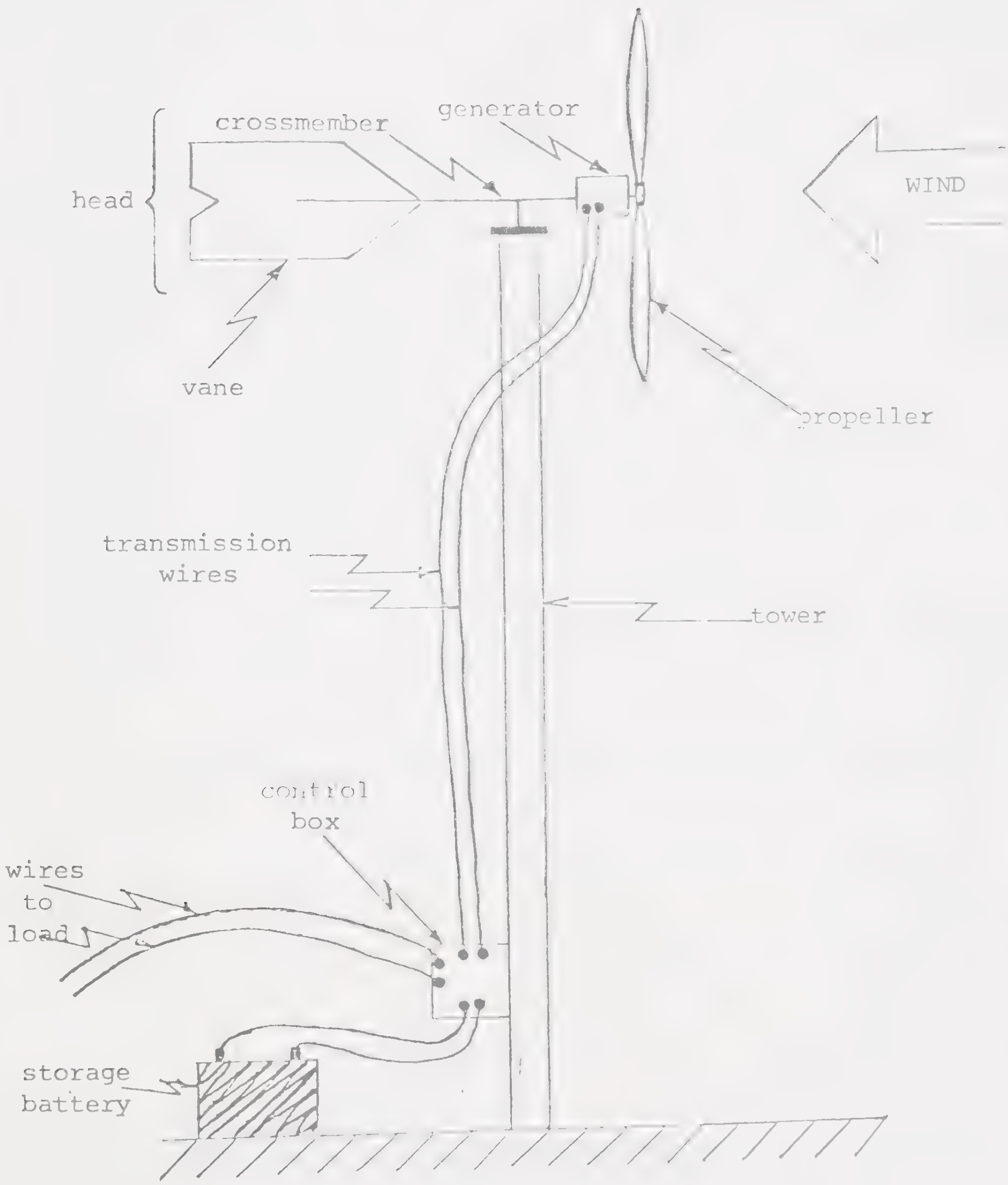

Figure 2 The Wind Electric System

Speed (rpm)	Regulator Output Voltage (volts)	Regulator Output Current (amperes)	Net Power Output (watts)	Comments
0	--	--	-90	Power produced is less than that required by the field coil.
250	--	--	-90	
500	--	--	-90	
750	--	--	-90	
1000	--	--	-60	
1250	--	--	0	Break-even point is at 1300 rpm.
1500	13.1	11	+144	
1750	13.8	19	262	
2000	14.0	18	252	
2250	14.1	18	254	
2500	14.2	19	270	Output becomes retively constant.
2750	14.3	19	272	
3000	14.2	19	270	
3250	14.3	19	272	
3500	14.2	19	270	
3750	--	--	--	
4000	14.2	19	270	
4250	--	--	--	
4500	--	--	--	
4750	--	--	--	
5000	14.2	19	270	Maximum safe speed

Figure 3 D.C. Generator Performance Data*

---

*Testing of typical D.C. Generator carried out under the supervision of Mr. S. Churchill of the Northern Alberta Institute of Technology, Edmonton.

Speed (rpm)	Regulator Output Voltage (volts)	Regulator Output Current (amperes)	Net Power Output (watts)	Comments
0	--	--	-25	Power produced is less than that required by the field coil. Break-even point is at 800 rpm.
250	--	--	-25	
500	--	--	-25	
750	--	--	-25	
1000	13.0	7.0	+91	
1250	13.5	14.0	189	
1500	14.1	21.0	296	
1750	14.5	25.0	363	
2000	14.9	28.0	417	
2250	15.2	31.0	471	
2500	15.4	33.0	508	
2750	15.6	35.0	546	
3000	15.6	37.0	577	
3250	15.7	37.5	589	
3500	15.8	39.0	616	
3750	15.8	40.0	632	Output becomes relatively constant.
4000	15.8	40.0	632	
4250	15.9	41.0	652	
4500	--			Maximum safe speed of alternator is 10,000 rpm.
4750	--			
5000	16.0	42.0	672	

Figure 4 Alternator Performance Data*

*Testing of typical Alternator carried out under the supervision of Mr. S. Churchill of the Northern Alberta Institute of Technology, Edmonton.

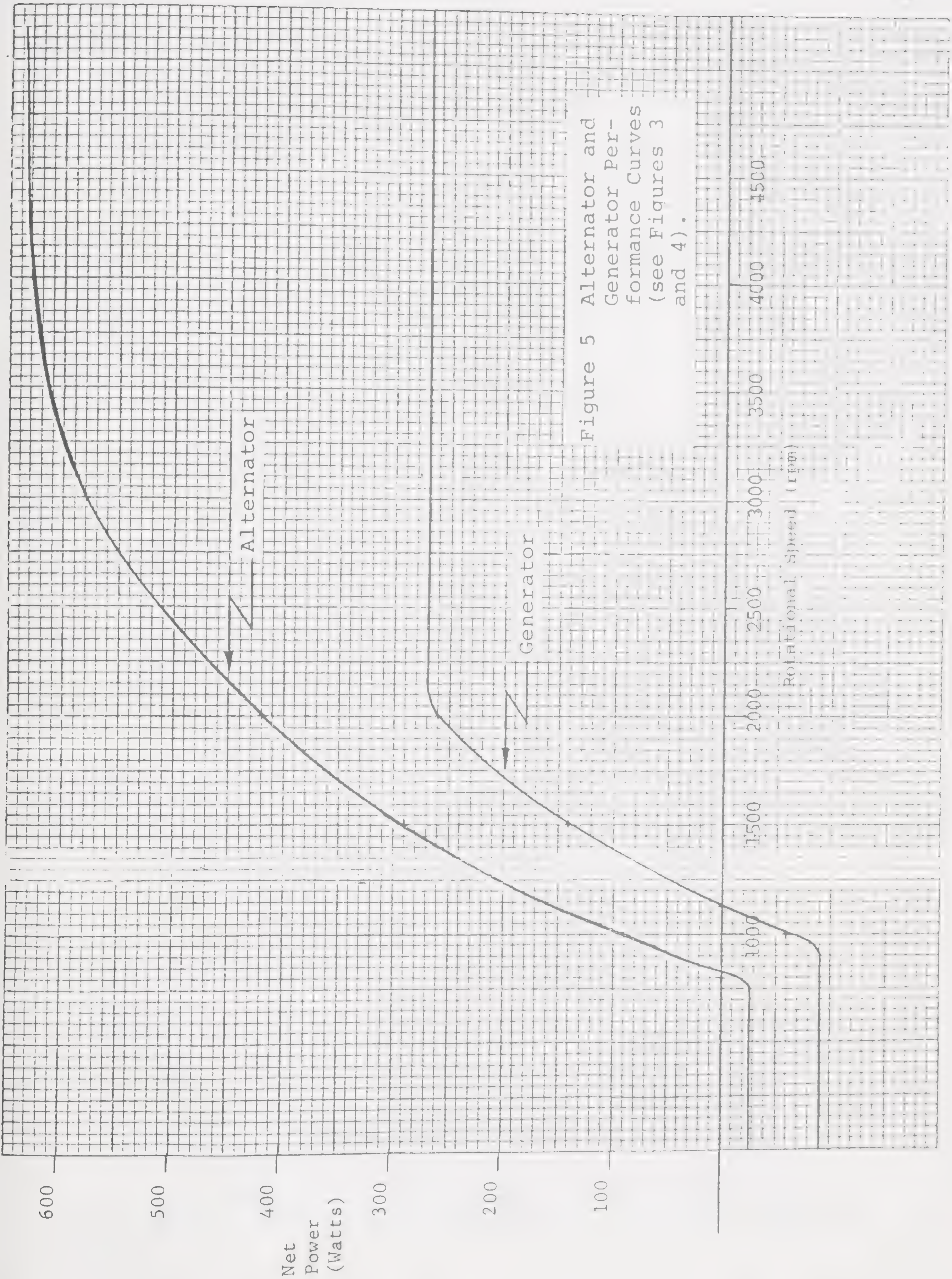

Figure 5 Alternator and Generator Performance Curves (see Figures 3 and 4).

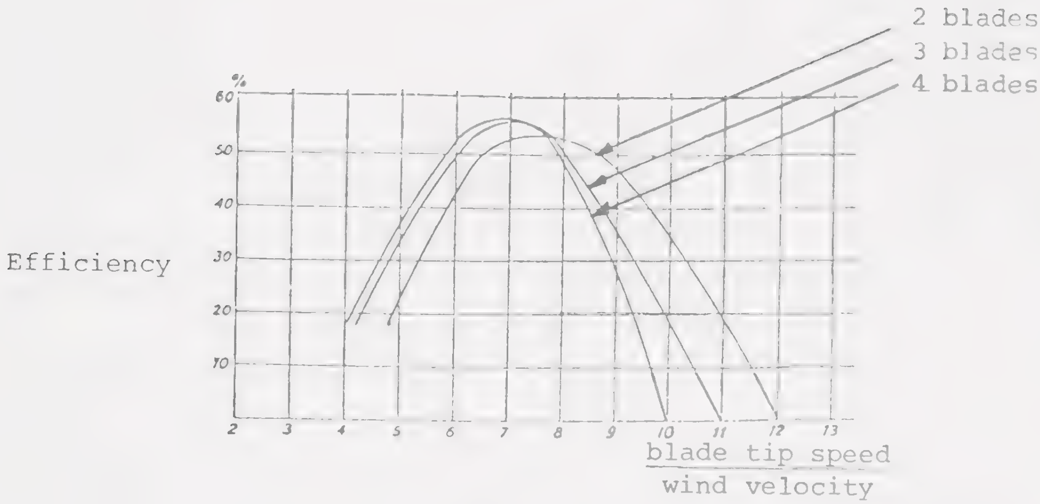

Figure 6* Effect of Number of Blades on Efficiency

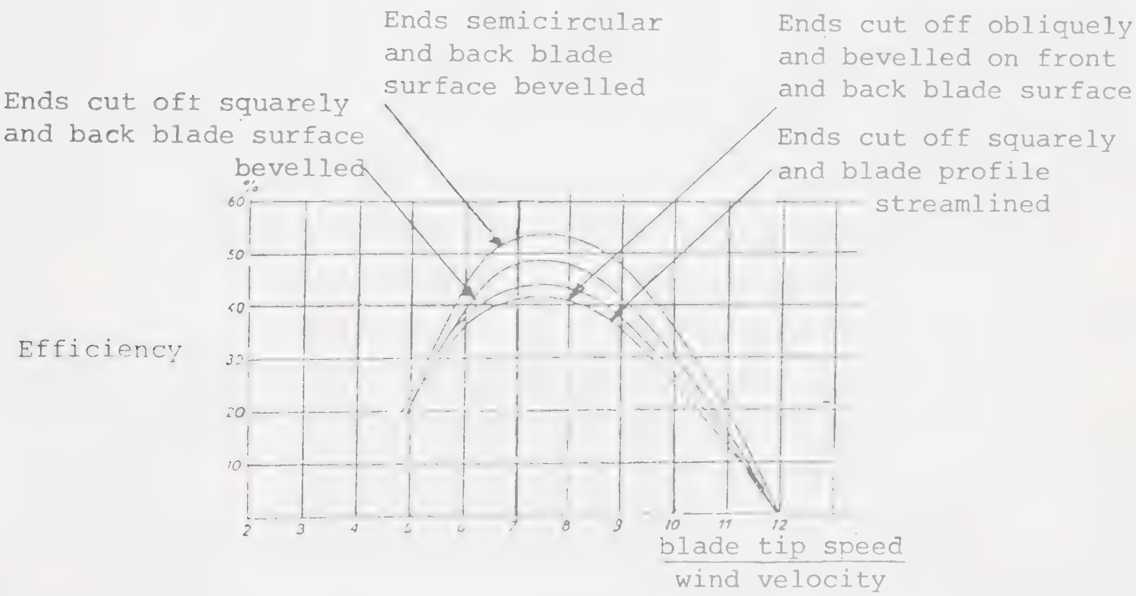

Figure 7* Effect of Blade Tip Profile on Efficiency

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*Both Figures 6 and 7 taken from contributions by J. Juul to: "Wind and Solar Energy--Proceedings of the New Delhi Symposium" (27).

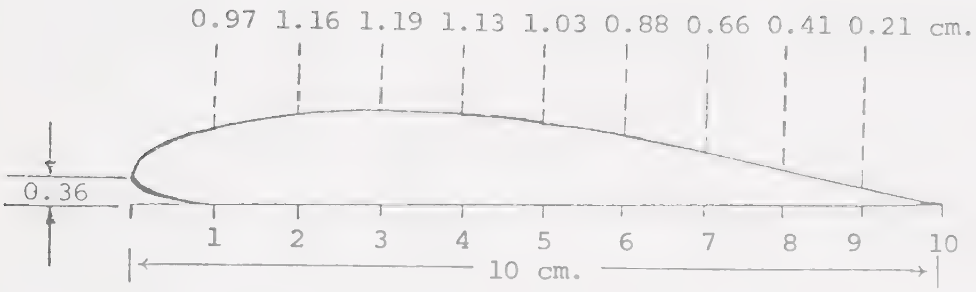

Figure 8* Propeller Blade Profile

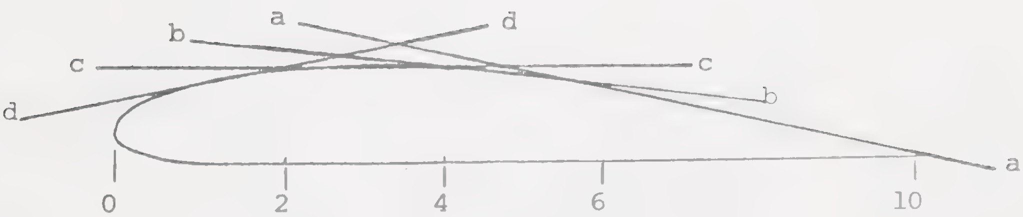

Figure 9 Blade Profile Approximation Using Straight Lines

The angle between the horizontal and a . . . a is 11.5°, the horizontal and b . . . b is 7.25°, c . . . c is horizontal and line d . . . d is -11.3° to the horizontal. Thus a . . . a approximates the profile from 6 to 10, b . . . b from 4 to 6, c . . . c from 2 to 4 and d . . . d from 0 to 2.

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*From (27).

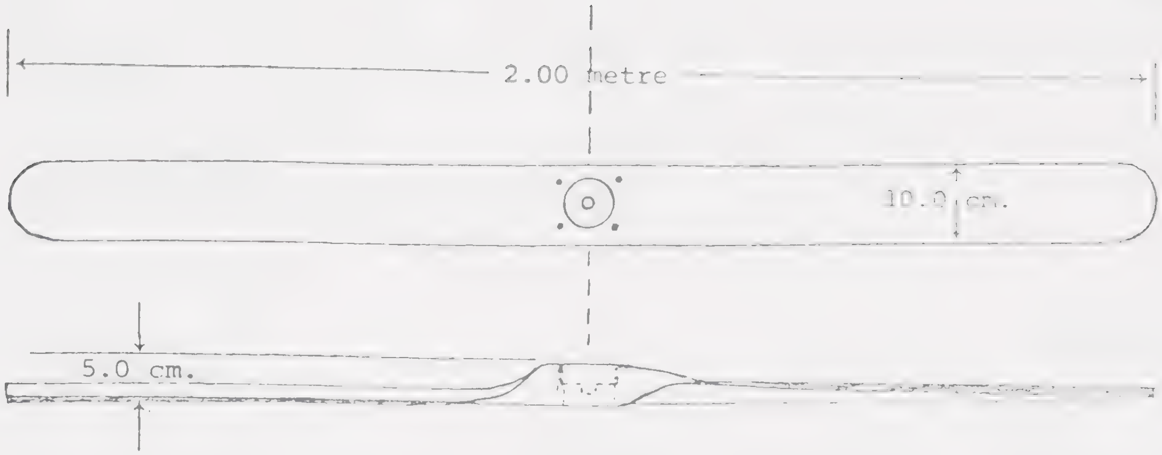

Figure 10 Propeller Dimensions

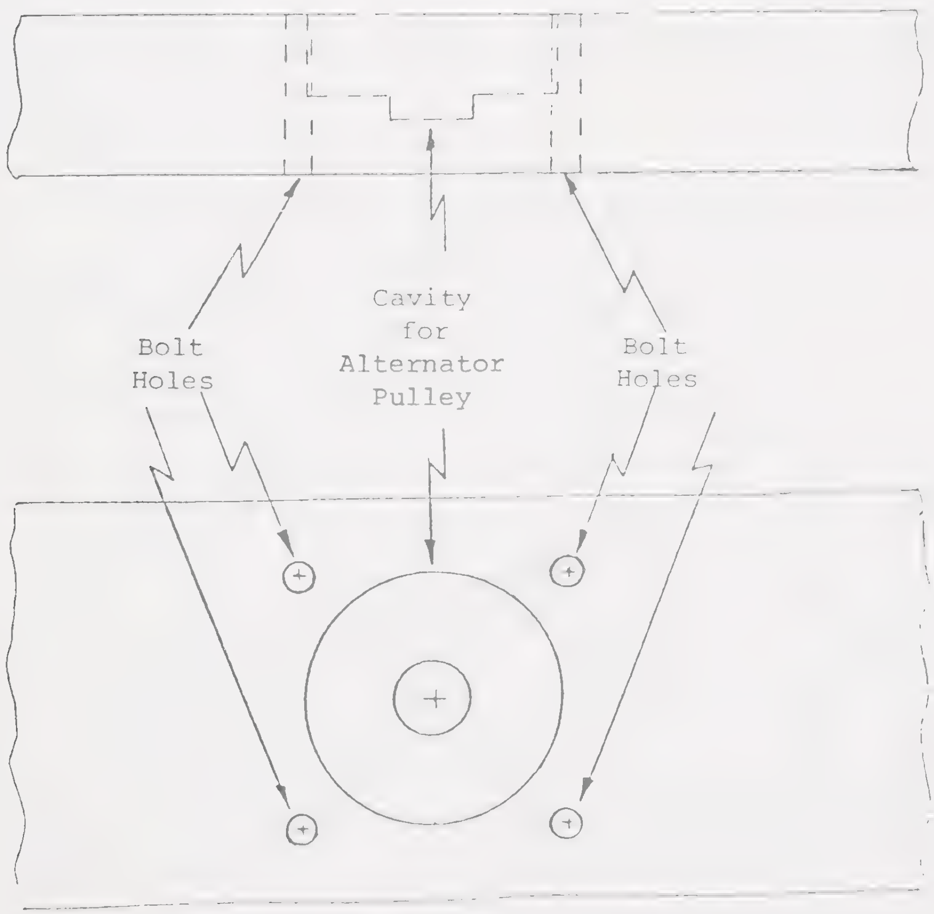

Figure 11 Propeller Hub Details

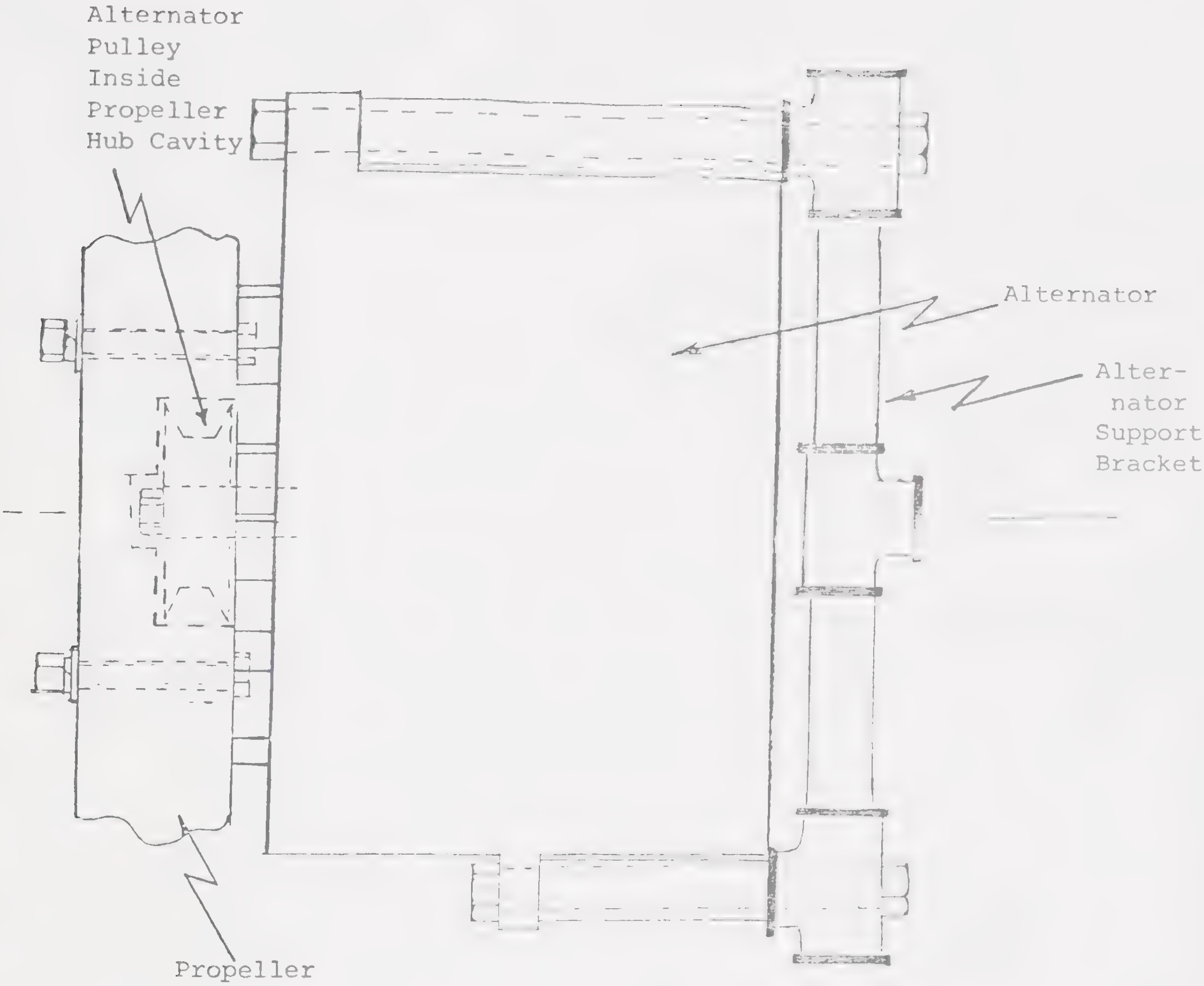

Figure 12 Alternator Mounting

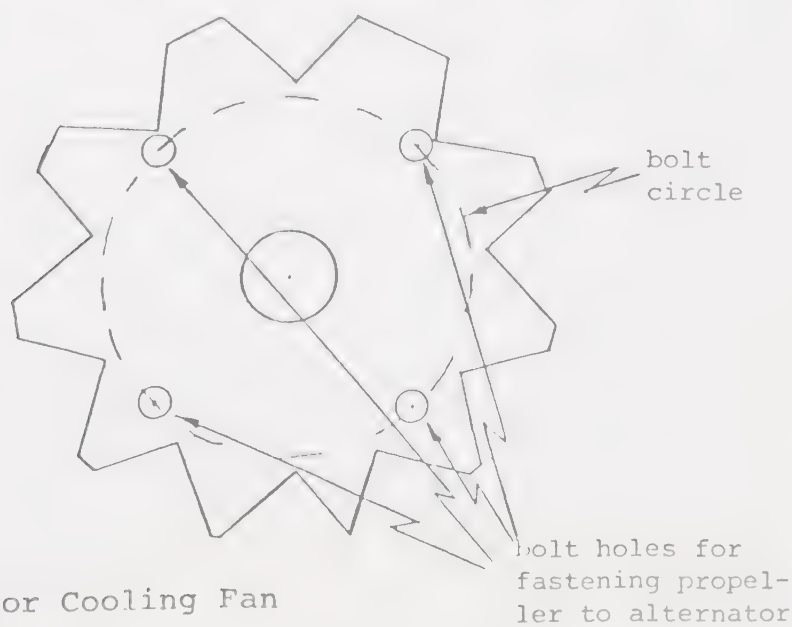

Figure 13 Alternator Cooling Fan

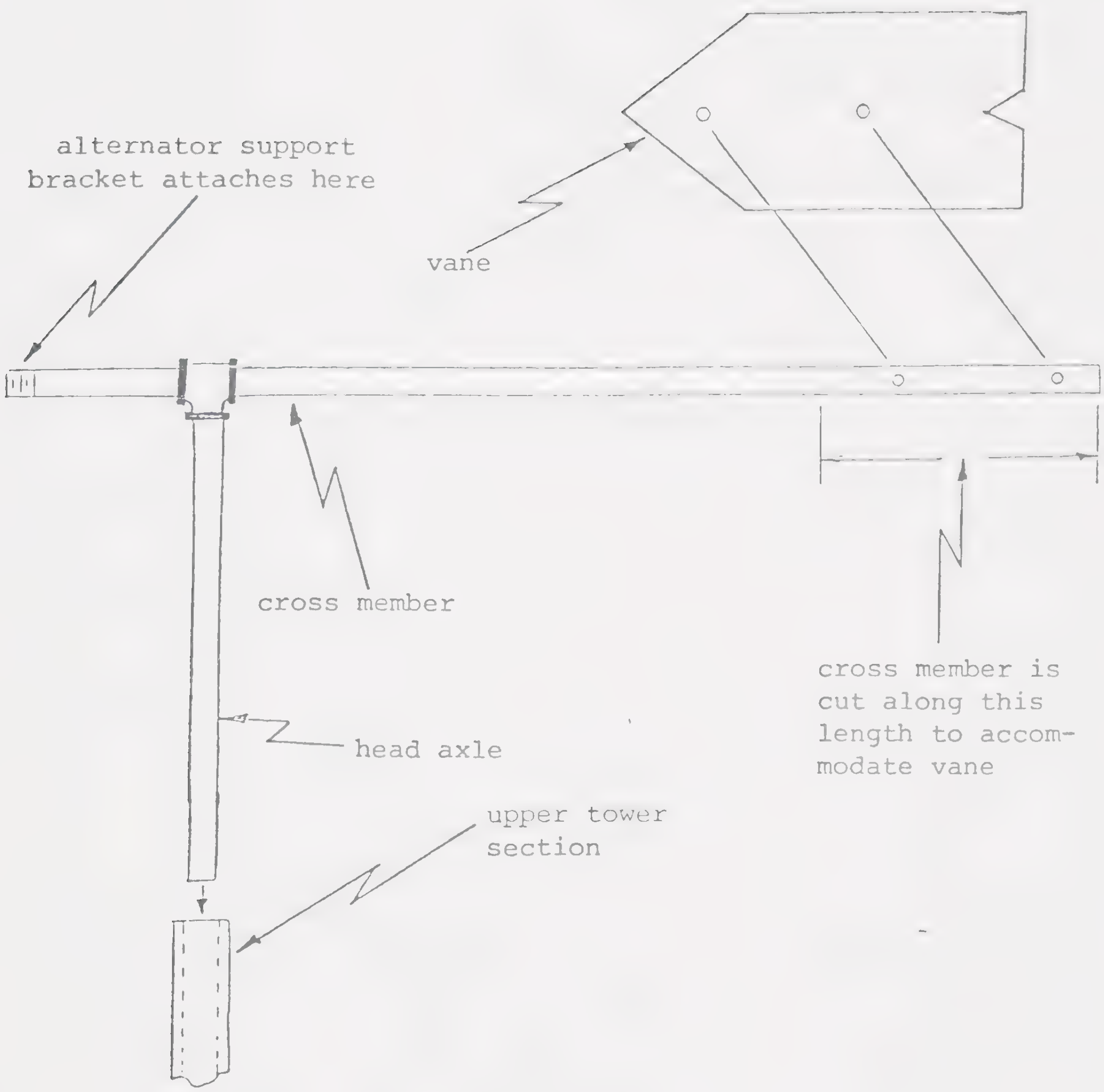

Figure 14 Head Components

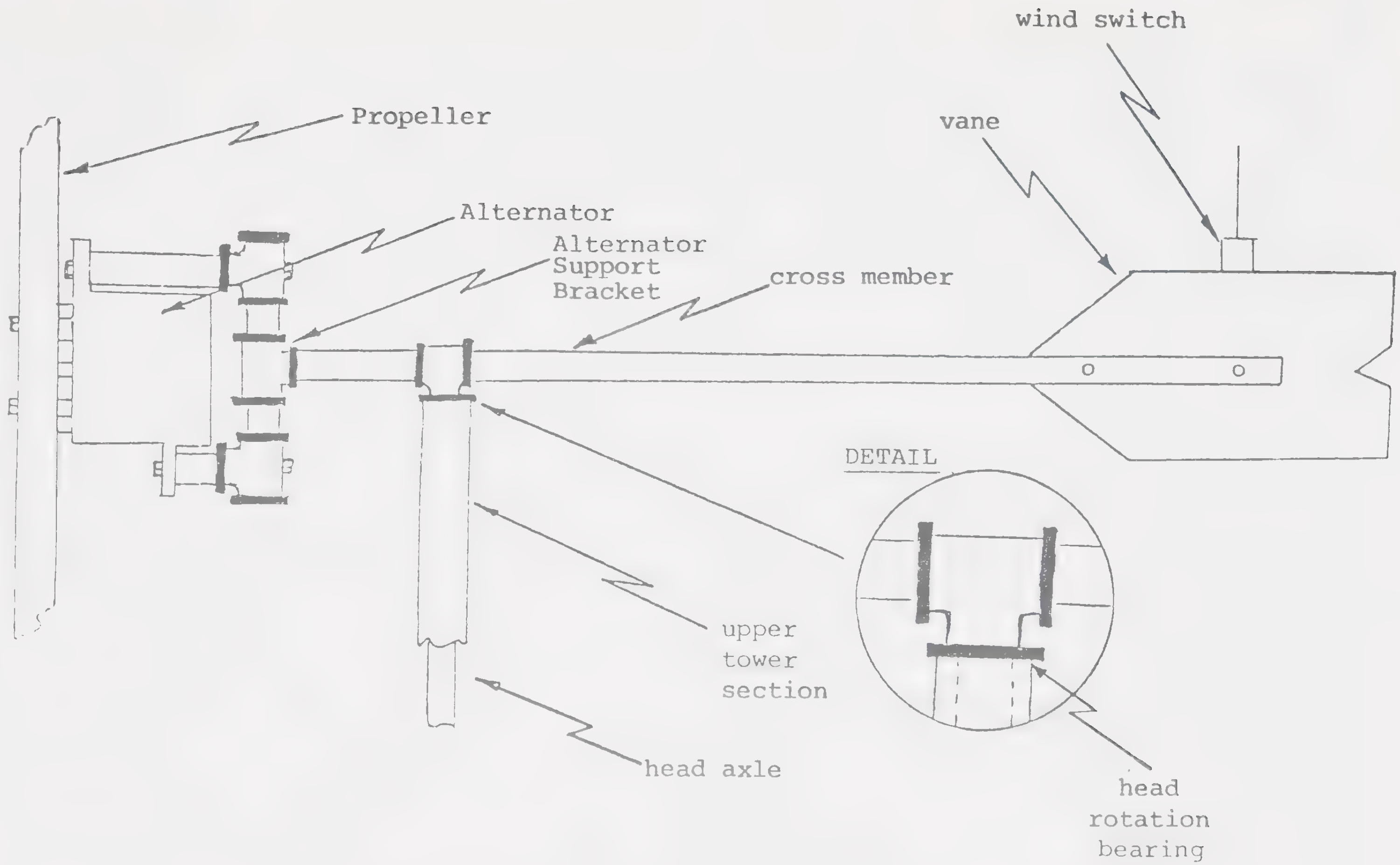

Figure 15 Head Assembly

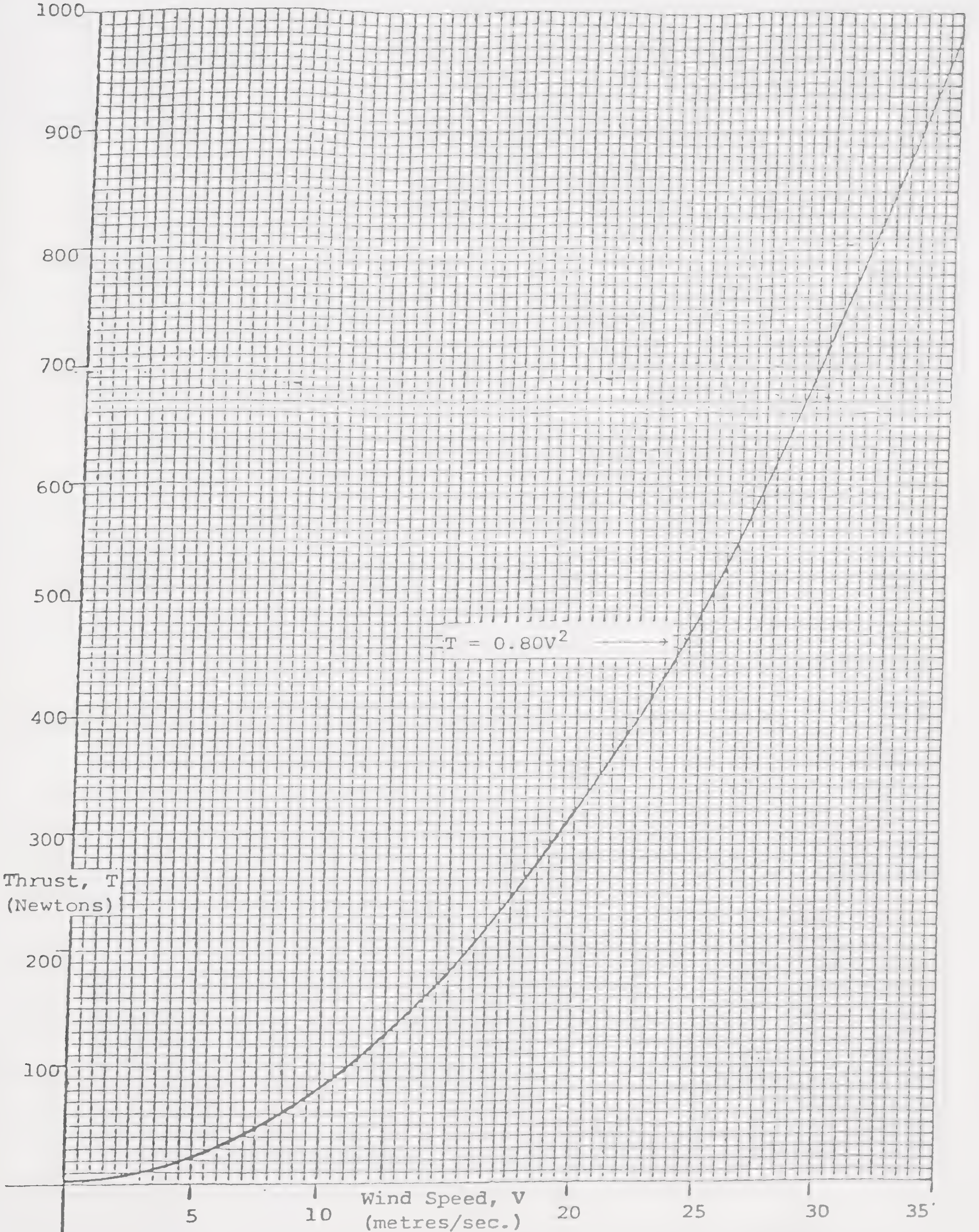

Figure 16 Wind Wheel Thrust versus Wind Speed

1	Tower Section Symbol	c	d	e	f	g
	Nominal Pipe Diameter (inches)	1.25	1.50	2.00	2.50	3.00
	Inside Diameter, D_i, (metres)	0.035	0.041	0.053	0.063	0.078
	Outside Diameter, D_o, (metres)	0.042	0.048	0.060	0.073	0.089
2	Thread Depth, H, (metres)	0.001	0.001	0.001	0.001	-0-
3	Effective Outside Diameter, D_e, (metres)	0.040	0.046	0.058	0.071	0.089
4	2nd Moment of Inertia, I, (metres^4)	$0.054 \cdot 10^6$	$0.079 \cdot 10^6$	$0.172 \cdot 10^6$	$0.476 \cdot 10^6$	$1.28 \cdot 10^6$
5	Radius of Gyration, r, (metres)	0.020	0.023	0.029	0.036	0.044
6	Moment Arm, L, (metres)	1.90	3.80	5.70	7.60	8.00
7	Maximum Moment, M, (newton-metres)	608	1216	1824	2432	2560
8	Maximum Stress, S, (newtons/cm.^{2})	22,500	35,400	30,800	18,400	8,800

1 as illustrated in Figure 18.

2 Thread Depth, H, is measured at effective thread length as illustrated in reference (21).

3 Effective Outside Diameter, D_e, equals the Outside Diameter, D_o, minus two times the Thread Depth, H, measured at the effective thread length

4 for circular cross-section pipe, $I = \frac{\pi}{64}(D_e^4 - D_i^4)$, from (12).

5 Radius of Gyration, r, equals half the Effective Outside Diameter, D_e.

6 illustrated for each section in Figure 19.

7 the Maximum Moment, M, is that which occurs in a 20 metre/second wind where M = T(L).

8 Maximum Stress, S, equals $(M \cdot r)/I$.

Maximum Allowable Stress - 60,000 psi or 41,500 N/cm.^{2}, from (21).

Figure 17 Stress Analysis of Tower in Vertical Position During 20 metre/second Wind.

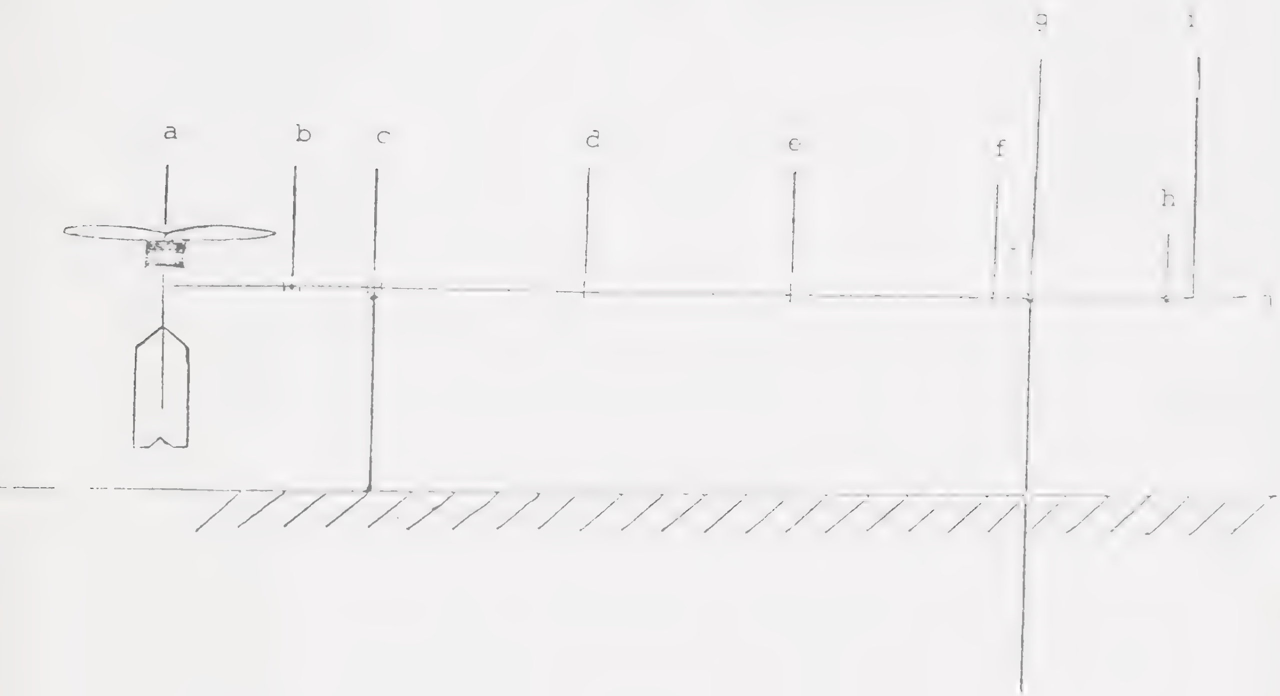

*Figure 18 Identification of Tower Sections by Letter

*Used in Figure 17 for tower stress analysis.

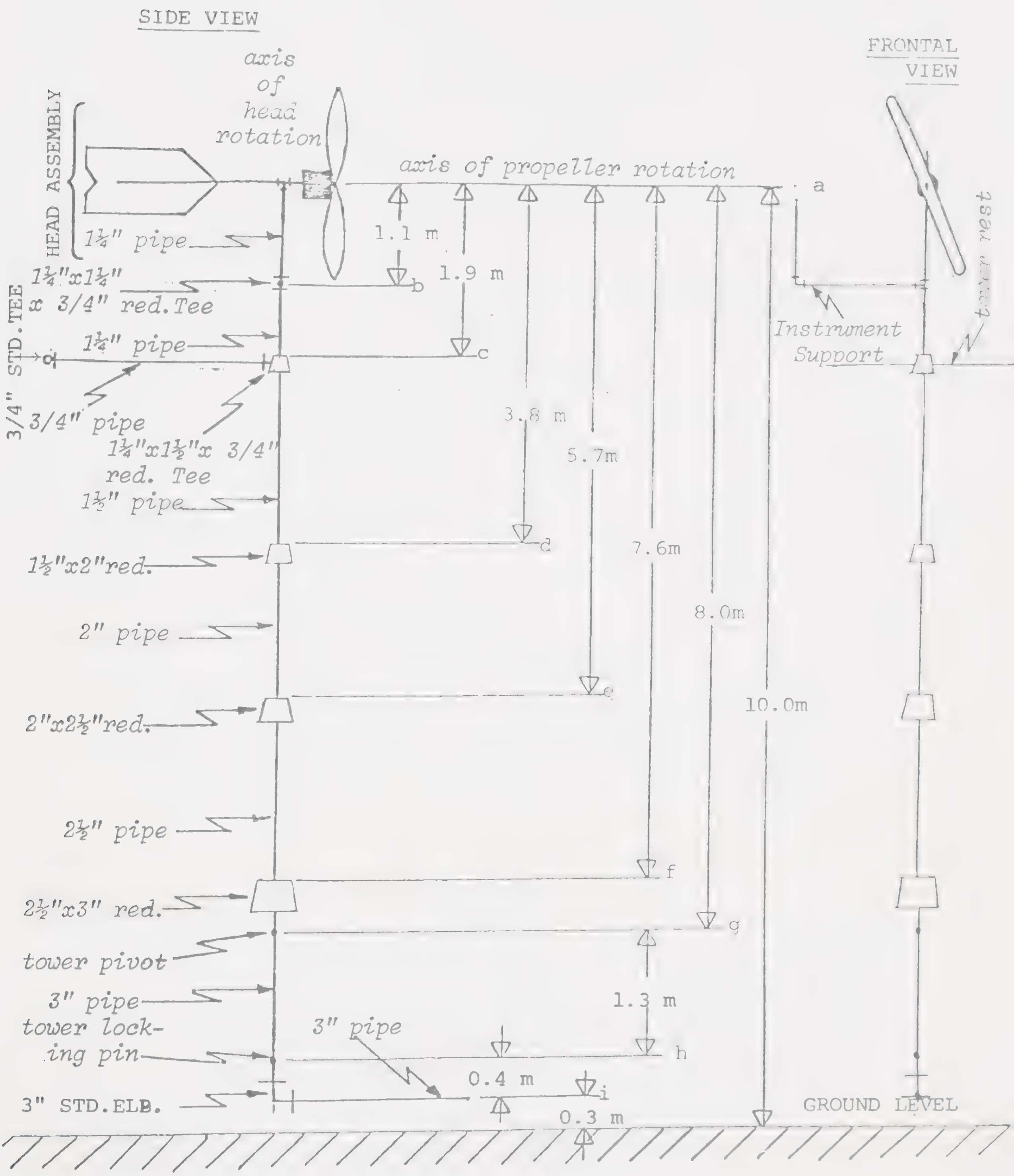

Figure 19* Tower Dimensions

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*Note that all connections are screwed and italics are used to indicate sections of particular interest.

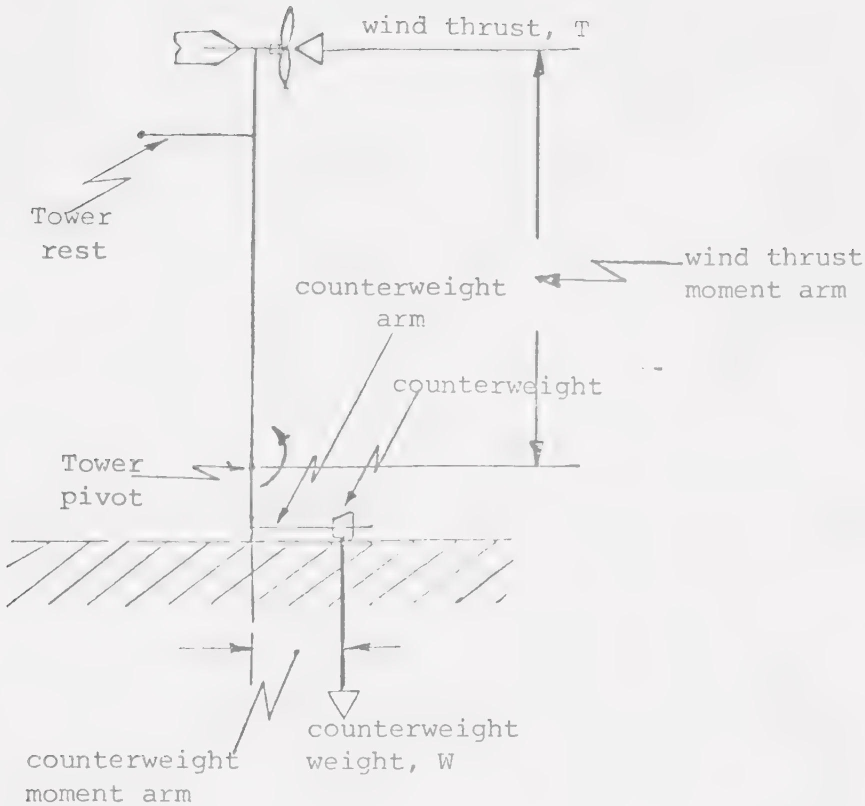

Figure 20 Force Diagram for Vertical Tower

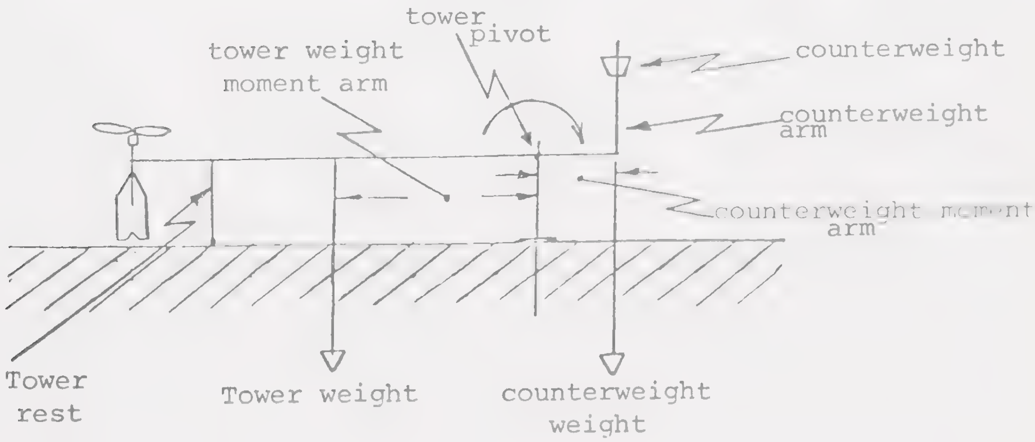

Figure 21 Force Diagram for Horizontal Tower

*1 Tower Section Symbol	Tower Component Description	Weight, W, (newtons)	Moment Arm (metres)	Moment, M_p, (N-m)
a	head assembly including alternator	123	8.0	984
a	propeller	12	8.0	96
a - c	upper tower section	69	6.9	476
b	instrument support	29	6.9	200
c	tower rest	30	6.1	183
c - d	tower section	59	5.2	307
d - e	tower section	98	3.3	323
e - f	tower section	177	1.4	248
f - j	lower tower section	216	-0.7	-151
j - i	counterweight leg	216	-1.7	-367
		W = 1029 N		M_p =2299 N-m

Therefore, the center of gravity of the tower in the horizontal position is at $\frac{M_p}{W} = \frac{2299}{1029}$ = +2.23 metres or 2.23 metres from the upper pivot towards the head. A counterweight mounted at the lower end of the tower as shown in Figures (23) and (24) would just balance the tower about the upper pivot if it were to weigh $\frac{1029\ (2.23)}{1.7\ \text{m}}$ N-m = <u>1350 N</u>.

In order that the tower is to remain stable in the horizontal position, a counterweight, W, of only 1000 newtons will be used.

Figure 22 Counterweight Specification by Moment Analysis

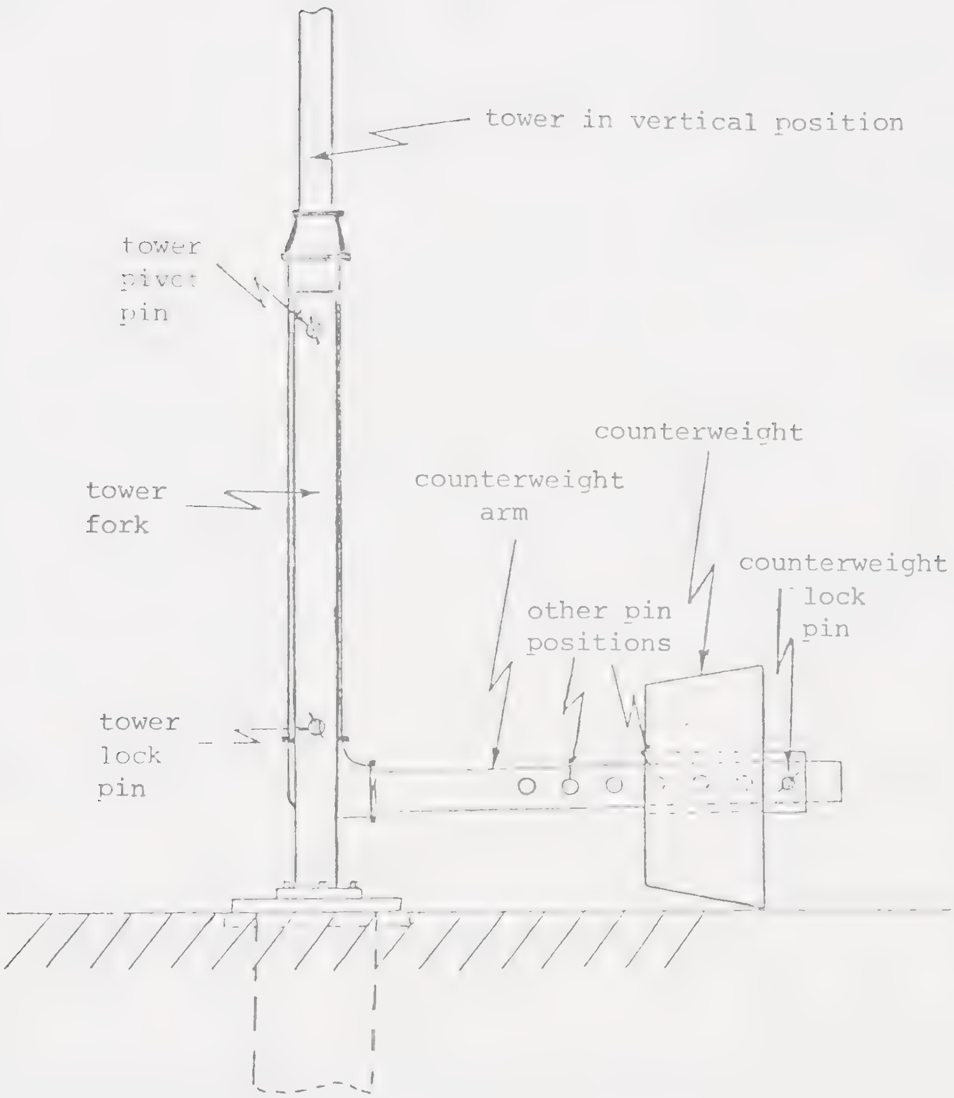

Figure 23 Counterweight Details for Tower in Vertical Position

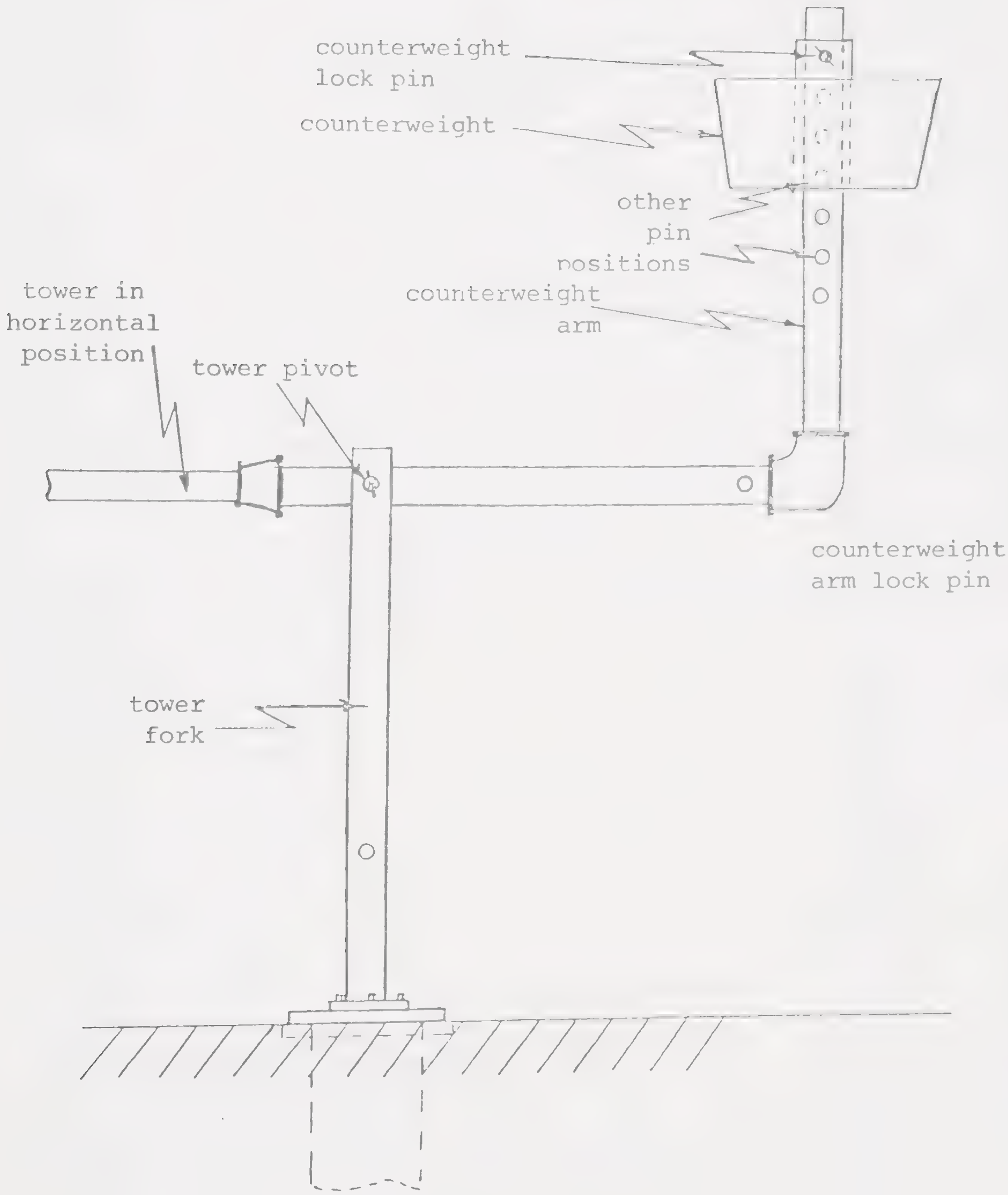

Figure 24 Counterweight Details for Tower in Horizontal Position

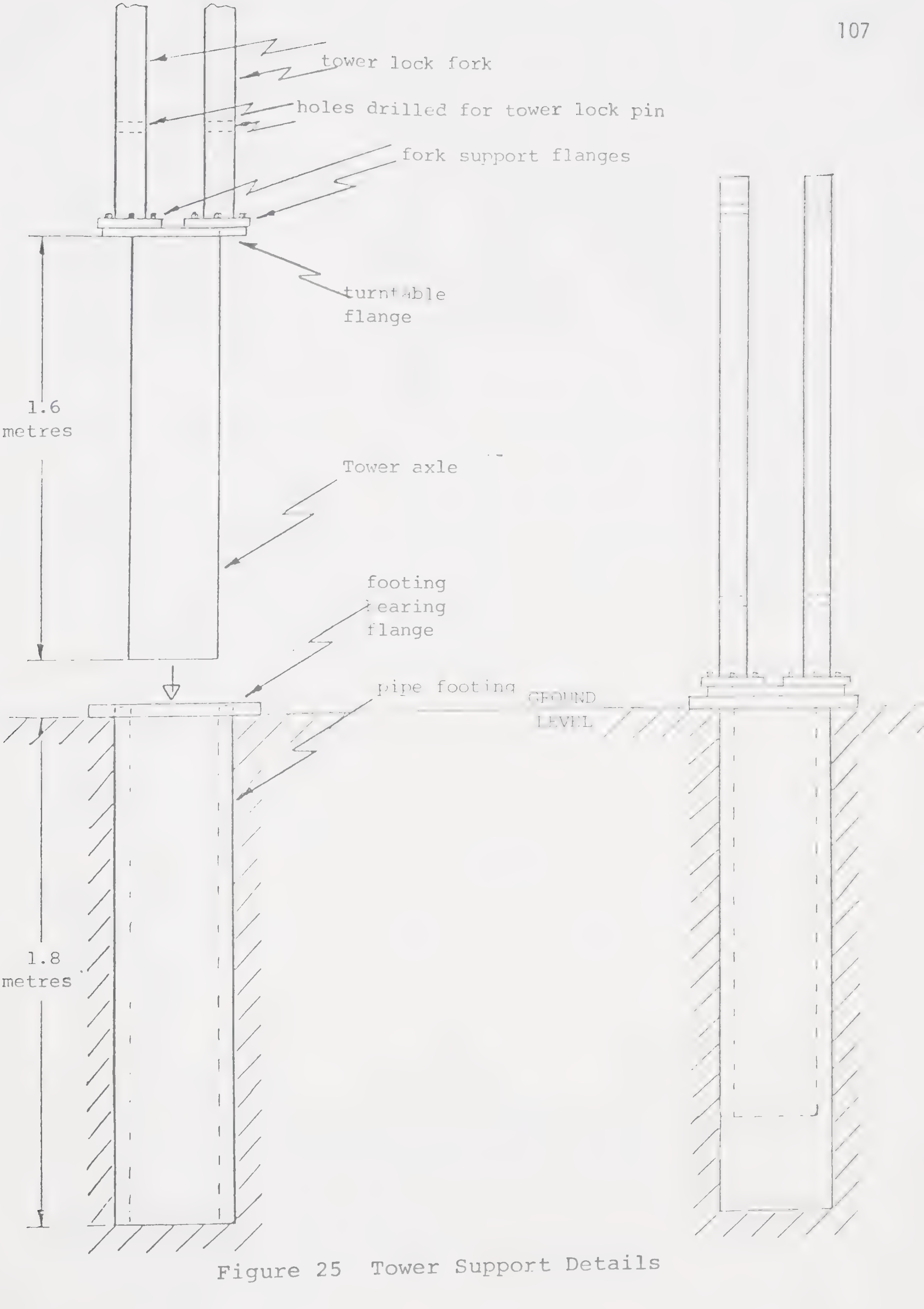

Figure 25 Tower Support Details

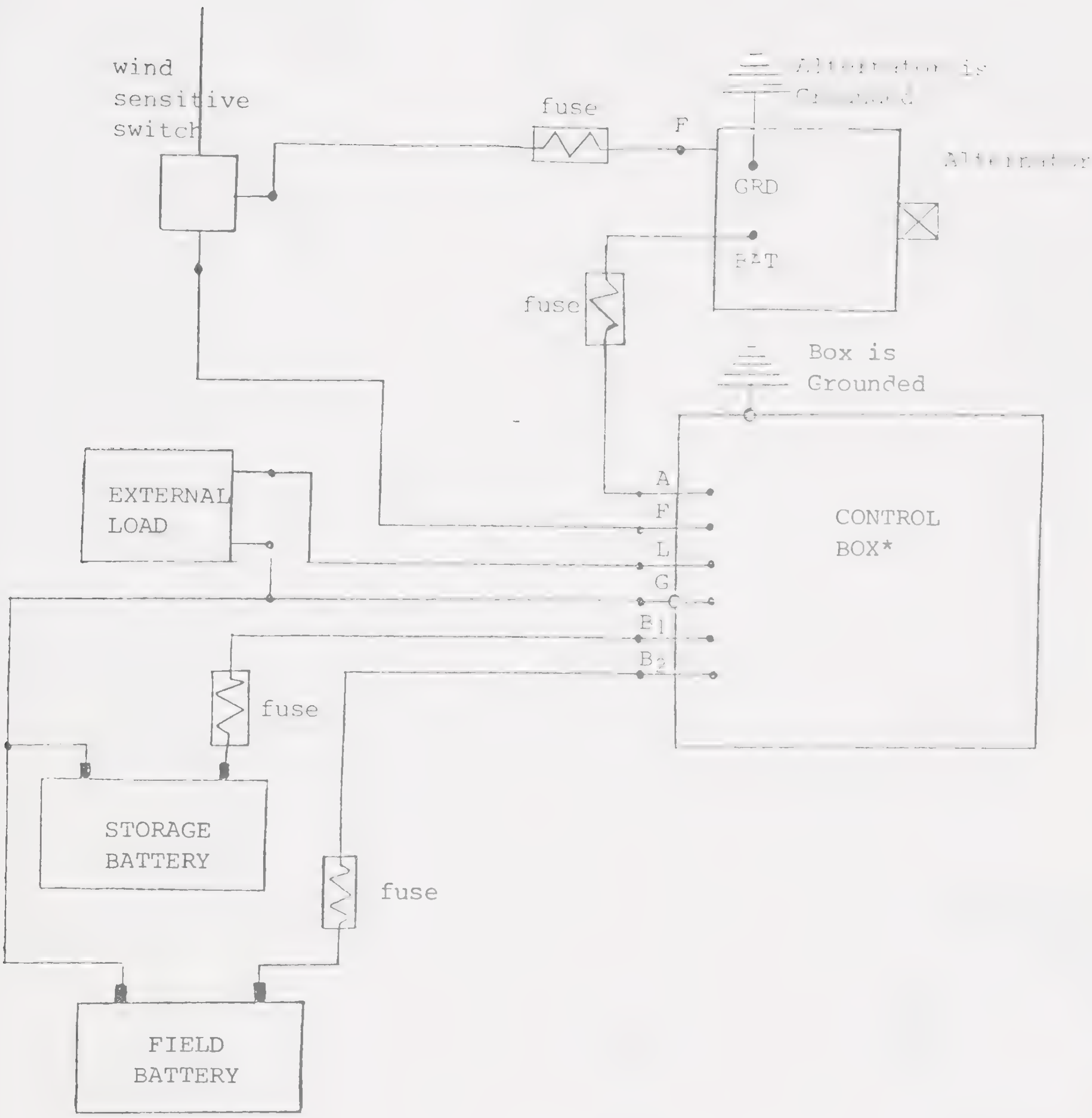

Figure 26 Electrical System Schematic

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*See Figure 27 for Detail of Control Box.

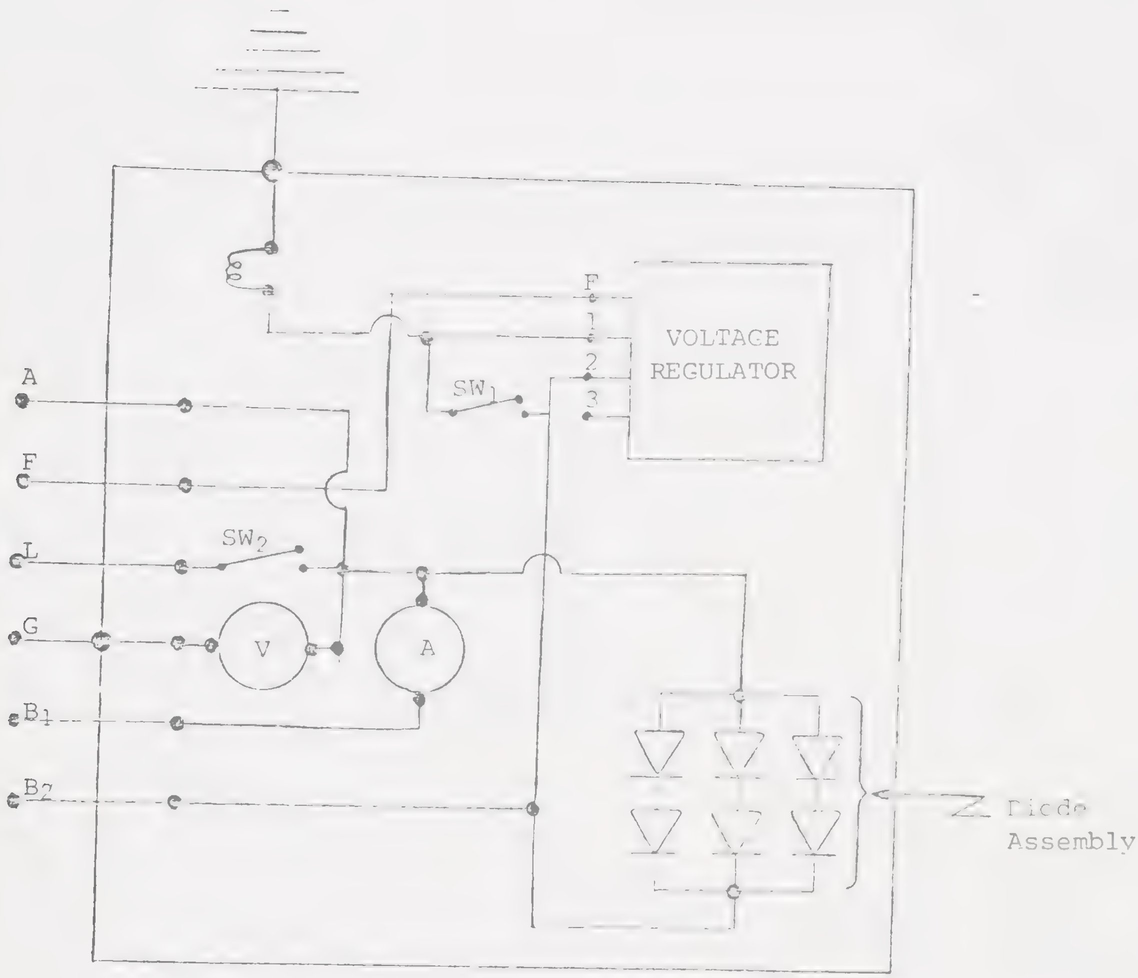

Figure 27 Detail Schematic of Control Box

(Note that switch 1 (SW_1) is used to turn the plant on and off and switch 2 (SW_2) is used to control the external load.)

Appendix 2

SYMBOL IDENTIFICATION

SYMBOL IDENTIFICATION

a = interference factor

A_f = projected area of footing (cm.^{2})

C = capital cost per unit power capacity ($/Kw)

C_p = power coefficient

D = windwheel diameter (metres)

d = displacement of air (metres)

E = specific output or annual energy output per unit power capacity (Kwh/Kw)

E_k = kinetic energy (Kwh)

f = density of air (Kg./metres^3)

F_c = soil compression force (newtons)

G = cost of energy ($/Kwh)

I = moment of inertia (metres^4)

M = maximum bending moment (newton-metres)

m = mass (Kg.)

n = rotational speed (rpm)

P = power available (Kw)

p = percentage applied in calculation of annual costs (%)

P_e = power extracted (Kw)

P_o = maximum extractable power (Kw)

P_r = pitch ratio

r = windwheel radius (metres)

r_g = radius of gyration (metres)

s = air speed (metres/second)

S_f = maximum stress (N/m^2)

S_s = soil compaction stress (N/cm^2)

T = thrust force (newtons)

t = time (hrs)

V = air flow volume ($metres^3$)

Φ = pitch angle (°)

τ = torque (newton-metres)

Appendix 3

FORMULAE

LIST OF FORMULAE

(A) $$P = \frac{E_k}{t}$$

(B) $$E_k = \tfrac{1}{2}ms^2(2.78 \times 10^{-7})$$

(C) $$m = V \cdot f$$

(D) $$V = \frac{\pi D^2 \cdot d}{4}$$

(E) $$m = \frac{\pi d^2 \cdot d \cdot f}{4}$$

(F) $$E_k = \frac{\pi D^2 \cdot d}{8} \cdot f \cdot s^2(2.78 \times 10^{-7})$$

(G) $$P = \frac{\pi D^2 \cdot d \cdot f \cdot s^2}{8t}(2.78 \times 10^{-7})$$

(H) $$\frac{d}{t} = 3600s$$

(I) $$P = 4.71 \times 10^{-4}D^2s^3$$

(J) $$P_o = 0.593P$$

(K) $$C_p = \frac{P_e}{P_o}$$

(L) $$P_o = 2.79 \times 10^{-4}D^2s^3$$

(M) $$P_e = 2.79 \times 10^{-4}C_pD^2s^3$$

(N) $$P = 2\pi T \cdot n(1.67 \times 10^{-5})$$

(O) $$D = \sqrt{\frac{P_e}{2.79 \times 10^{-4} C_p \cdot s^3}}$$

(P) $$T = 2\pi r^2 \cdot f \cdot V^2 \cdot a(1-a)$$

(Q) $$T = 0.80V^2$$

(R) $$S_f = \frac{M \cdot r_g}{I}$$

(S) $$G = \frac{P \cdot C}{100E}$$

Appendix 4

PLATES

Plate I Carving the Propeller

Plate II Detail of Blade Profile (shown with windward side up)

Plate III Setup for Bench Testing of Propellers

Plate IV Using the Stroboscope to Determine Propeller Rotational Speed

Plate V Wire Stiffened Propeller (shown mounted for testing)

Plate VI Detail of Stiffener Bracket

Plate VII Detail of Wire Attachment to Blade Tip

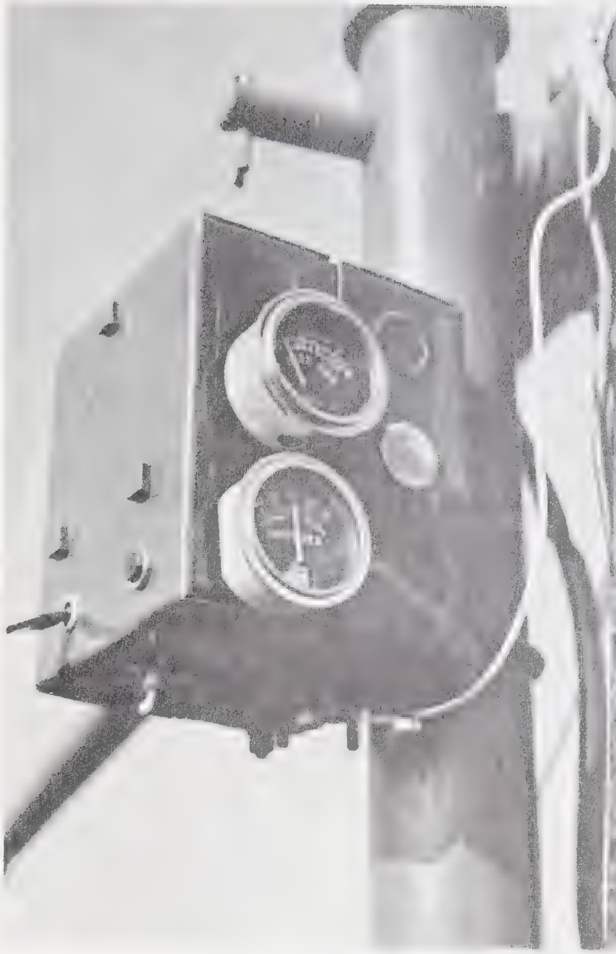

Plate VIII Control Box

Plate IX Control Box Mounted to Tower Fork

Plate X Inside the Control Box

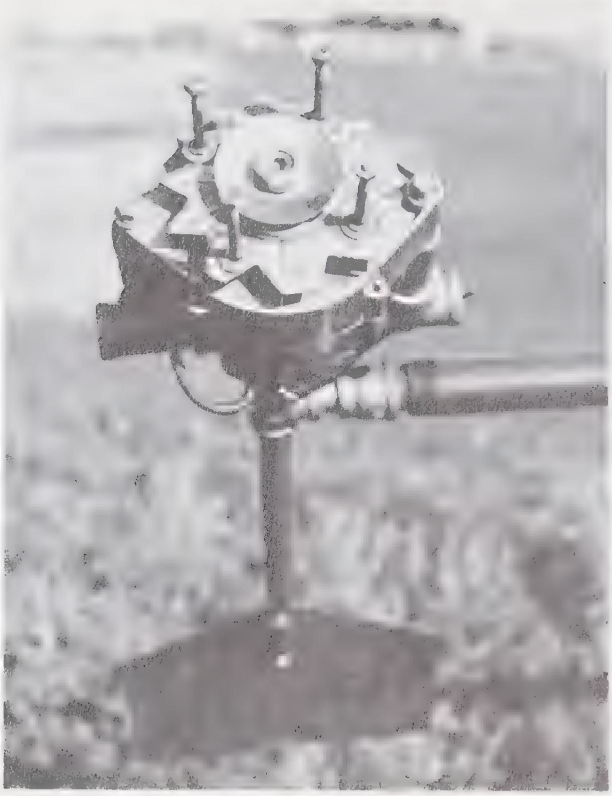

Plate XI Head Assembly
(Note bolt arrangement used to attach the propeller.)

Plate XII Alternator Mounting and Wiring

Plate XIII Counterweight
(Shown mounted on counterweight arm with the tower vertical)

Plate XIV Counterweight
(Shown with tower horizontal)

Plate XV Prototype Propellers

The propeller on the left, carved from White Pine, was the first one made and had serious vibration problems. The second propeller from the left, also carved from White Pine, was made thicker near its blade roots to increase stiffness but this did not solve the vibration problem. The third propeller, shown mounted on the alternator, was made from Eastern Birch which proved stiff enough to avoid vibration and this one was used for testing.

Plate XVI Run-of-the-Wind Meter
(Stopwatch is shown to indicate that time intervals must be measured in order that average wind speed be known.)

Plate XVII Launching the Prototype
(Note that the tower can be easily erected or lowered by one man.)

Plate XVIII Prototype in Operation

Plate XIX Top Section of Prototype